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Jisun Kim *Editors*

# Research and Technology Management in the Electricity Industry

## Methods, Tools and Case Studies

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## Methods, Tools and Case Studies

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# Contents

# Introduction

This book originated through the establishment of the Technology Innovation (TI) office at Bonneville Power Administration (BPA). As new technologies got integrated to grid, they brought new challenges with them. To alleviate the resulting issues, BPA had established the TI office and assigned Terry Oliver as the Chief Technology Innovation Officer. One of the first things that Terry did was to start collaborating with the Engineering and Technology Management Department at Portland State University to develop the appropriate methods to run his office. This book is one of the products of this collaboration.

This book has three parts. The first part introduces the methods used for technology planning. The second part provides applications from the electricity industry. Finally the third part focuses on the innovation through these technologies.

We are grateful to the authors of the chapters in this book. They had gone out to find data and had analyzed it and provided extremely useful examples.

## Technology Planning

The first chapter provides an introduction to methods used in strategic technology planning. In addition to the list and nature of the methods, the chapter also provides a comprehensive list of references for each methodology. The second chapter focuses on multi criteria decision making tools. Specifically the electric industry has to focus on multiple issues ranging from economic to political; therefore review of these tools is critical. However political and social issues are mostly qualitative and require expert opinion. The third chapter reviews methods focusing on quantifying expert judgments. Final chapter of this part reviews technology forecasting methods.

## Applications

This part provides applications of the methods provided in the earlier part. The first application introduces use of multi criteria decision making for photo voltaic solar technology. The following chapter provides an application of expert judgment quantification for wind energy. Chapter 7 provides an application of technology assessment and roadmapping for transmission technologies. Last three chapters explore future scenarios. Use of patent analysis for technology forecasting is used in Chap. 8 to evaluate wind turbine technologies. Adoption of energy efficiency related technologies is explored in the last two chapters of this part. As several electric utilities are adopting renewable energy sources for electricity generation or investing into energy efficiency instead of building another power plant, these chapters will be useful to many in building evaluation schemes for their plans.

## Technology Innovation

After technologies are evaluated and selected, organizations need to focus on innovating through products and services. This part provides cases demonstrating critical issues. Chapter 11 explores the strategic balance in research and development. Chapter 12 provides an innovation metric to assess green buildings. Identification of customer preferences is demonstrated in Chap. 13. Chapter 14 provides an insight into innovation in a rural area while Chap. 15 provides an insight into the role of policies and other issues for energy efficiency innovations to be successful.

# Methods and Tools Applied in Strategic Technology Planning

**Yulianto Suharto and Tugrul Daim**

**Abstract** The relationship between strategic technology planning and the overall business strategy has been one of the growing fields that attract much interest both from academic and industry points of view. The increasingly important role that technology plays in today's business success is well established. The ability to create, modify and maintain the alignment of technology planning to the overall business strategy—as market/business conditions change, new opportunities arise, and new capabilities are developed—can define the success or failure in the market. An increasing number of studies have been carried out over the years, contributing to the development of strategic technology planning literature. However, there has been no effort made to present an overview of the methodologies and tools that have been cited in technology planning literature. This chapter surveys technology plan development using literature review and classification of articles from 1970–2010 with keyword index in order to explore how technology planning methodologies and applications has developed in this period. The main content of the chapter is related to the works published in leading international journals that involve certain research methodologies or techniques.

## 1 Introduction

Strategic technology planning is an important area and critical in business. It requires a company to utilize its core competences to outperform its competitor. The ability to create, modify and maintain the alignment of technology planning to

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the overall business strategy—as market/business conditions change, new opportunities arise, and new capabilities are developed– can define the success or failure in the market [1, 2, 3].

Although strategic technology planning has been developed over the past four decades and found its value in many strategic technology related problems, there is a tremendous effort from scholars in finding more effective methods. This chapter is an effort to capture those developments.

In this chapter the journal articles are reviewed with a particular interest in identifying what approaches, methods, and tools have been presented or employed in strategic technology planning research. An index search for strategic technology planning related articles was carried out in the leading journals of the field of management of technology (MOT). These journals were selected based on the two articles that studied the citations of leading journals most cited in the MOT literature [4], such as Technological Forecasting and Social Change, International Journal of Technology Management, and IEEE Transactions on Engineering Management. An important point that needs to be considered is that this chapter aims to capture all methods and tools applied in strategic technology planning that relates to overall business strategy.

The research method of this chapter is deep analysis of available literature of related fields based on a deductive approach and a content analysis method. The literature survey is based on a search for the keyword index 'technology planning' on the Business Source Premier, Compendex/Engineering Village online database and Proquest database, from which 21,148 articles from 1970–2010 were found on March 1 2011.

After topic filtering, there were 3662 articles related to the keyword 'strategic technology planning methodologies and frameworks' and 249 of these were connected to the keyword 'strategic technology planning methodologies and corporate strategy'. Out of the 249 reviewed articles, 76 are cited in this chapter. Based on the scope of 76 cited articles, this chapter surveys and classifies strategic technology planning methodologies using three categories: market analysis approach, technology analysis approach and combined approaches of market and technology.

## 2 Defining Strategic Technology Planning

Strategic technology planning is defined as the process of determining which technology is not yet adopted that will have a strategic impact on the company. Strategic technology planning is becoming more critical with the rapid development and obsolescence of the technologies. Most companies are facing an increasing and fiercer competitive challenge due to globalization. Basically, there are two reasons behind this phenomenon. First, competition is caused by other companies operating more effectively. Second, the company lost its competitive advantages by cutting back its research and development investments.

Strategic technology planning represents all capabilities that require investment or alignment to achieve the key product attributes defined in the product strategy. These technologies or capabilities come from either internal development or external sources. The specific architecture of this section will depend on how technology is managed in the business, whether by cross-business technology platforms or by business/product-specific technology groups [3].

Strategic technology planning activities–within a corporate level–are often implemented by applying integrated planning instrument, which allow firms to consider both technology-oriented and product-oriented aspects [5].

The literature of strategic technology planning is considered relatively rich at the corporate level [6]. However, dealing with all dimensions and elements of corporate strategy is not the aim of this chapter. For the purpose of this chapter, the literature review and its content analysis will be divided into three categories; market analysis approach, technology analysis approach and combined approaches of market and technology.

## 3 Market Analysis Approach

From the market standpoint, scholars have been conducting several valuable researches in an attempt to formulate methodologies or frameworks for strategic technology planning. Figure 1 described the number of publication lists on strategic technology planning in regards to market analysis approach.

*The experience curve* is one of the well-known approaches in technology planning. The experience curve states that the more frequent a task is performed; less time would be required on subsequent iterations [7]. The reason for why experience curve effect applies, of course, is the complex processes of learning

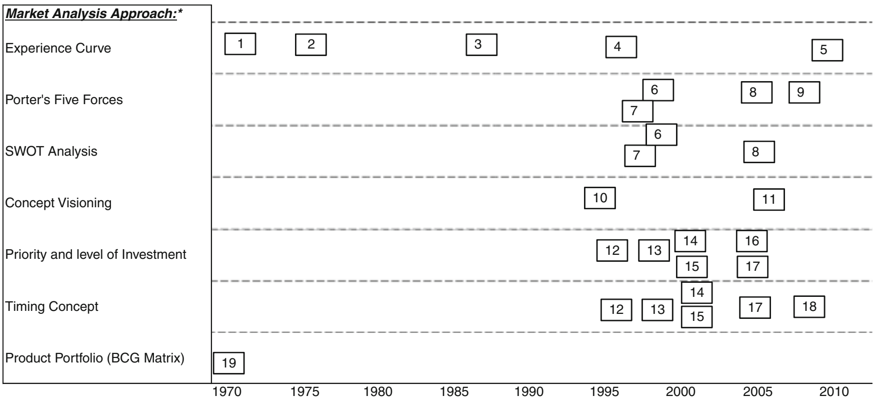


**Fig. 1** Publications on strategic technology planning: market analysis approach (in order of publication time)

involved. The consequences of the experience effect for businesses have been examined by many marketing strategist. They concluded that because the relatively low cost of operations is a very powerful strategic advantage, firms should capitalize on these learning curves. The reason is increased activity leads to increased learning, lower costs, lower prices, increased market share, and eventually can increase profitability and market dominance [8–12].

*Porter's Five Forces* is a framework for industry analysis and business strategy development introduced by [13]. This framework identifies and analyzes five competitive forces that shape every industry, and helps determine an industry's weaknesses and strengths, which include: (1) competition in the industry, (2) potential of new entrants in the industry, (3) power of suppliers, (4) power of customers, and (5) Threat of substitute products. Porter's framework is an extension to the more generic framework on SWOT analysis, a technique that is credited to Albert Humphrey [14–16].

Passey et al. [17] worked with the term *concept visioning* coupled with multiple *scenario building* as part of an innovation roadmap in the technology planning framework. Both terms were utilized to formulate product innovation and to provide effective communication with the required stakeholders. Passey et al. [17] also argues that these tools are necessary to identify the market context, including varying and emerging markets and build the business case to justify resources for further development [17, 18].

Friar [19] argues that strategic technology planning should include: selection, resource allocation and organizing technological assets, which support long-term strategic direction of the company. Based on the work of Christensen [20], Hax and Majluf [21], and Coombs and Richards [22], technology planning can be seen as a tool for:

1. providing overall strategic guidance of the corporate technology base and innovative efforts,
2. providing parenting value to divisions and business units in their innovative efforts,
3. assuring a proper balance and alignment between short-term, incrementally innovative efforts (exploitation) and long term explorative efforts; and
4. Increasing horizontal technology transfer and sharing, as well as synergy and coordination in research and technological innovation between divisions and business units.

These arguments also meant that strategic technology planning—in relation to market analysis—has to deal with the concept of *level of investment involved* [20, 21, 23, 24] and *timing concept* [20, 21, 23, 25–27].

*Market portfolio*—also known as product portfolio [28]—analysis is probably one of the most widely used tools in the field of strategic technology planning with main concern on the market side. This concept was developed since diversified companies were facing two major problems at that time: (1) increasingly complex strategic technology planning process; (2) competition becomes fiercer than ever. Therefore, companies had to find new ways to assure an effective and efficient

**Table 1** List of author(s) as indicated in Fig. 1

| No | Authors | No | Authors |
|---|---|---|---|
| 1 | Gates and Scarpa [8] | 11 | Passey et al. [17] |
| 2 | Ebert [11] | 12 | Hax and Majluf [21] |
| 3 | Globerson and Millen [12] | 13 | Christensen [20] |
| 4 | Hanakawa et al. [10] | 14 | Christensen [25] |
| 5 | Plaza et al. [9] | 15 | Edler et al. [23] |
| 6 | Menon et al. [14] | 16 | Larsson [24] |
| 7 | Hill and Westbrook [16] | 17 | Pieterse [27] |
| 8 | Phaal et al. [15] | 18 | Grienitz and Ley [26] |
| 9 | Porter [13] | 19 | Ernst et al. [28] |
| 10 | Latham and John [18] | | |

management of the company's resources. The BCG matrix was developed for this purpose and still considered as the most widely known and implemented approach [29, 30].

Number in a box refers to author(s) as listed in Table 1.

## 4 Technology Analysis Approach

Different methodologies and techniques have been developed by scholars in their attempt to manage and plan the company's technology. This chapter categorized those methodologies and techniques into: bibliometric, technology acquisition, organizing of technology management, technology integration, soft system methodology, database tomography, technology development envelope (TDE), patent analysis, and analytical hierarchy process (AHP). The publication list is shown in Fig. 2.

*Bibliometric* methods are utilized by Kostoff and Schaller [31–33] to explore the development of strategic technology planning on roadmapping foundation [3]. Hax and Majluf [21] demonstrated that technology planning decisions are not solely based on selection, resource allocation and organizing technological assets. Technology planning also discusses *technology acquisition* methods [20, 25, 34, 35], technology intelligence, technology organization and managerial infrastructure; and timing of technology introduction [20, 23, 26].

The use of *Soft System Methodology* (SSM) in the area of technology planning is well documented. SSM was originally developed in the late 1960s at the University of Lancaster in the UK [36, 37]. At first, it was seen as a modeling tool, but in later years it has been seen increasingly used as a meaningful learning development tool. In combination with technology roadmapping methods, Okutsu et al. [38] managed to apply the combined method into the area of technology planning and implement it to engineering laboratory's application.

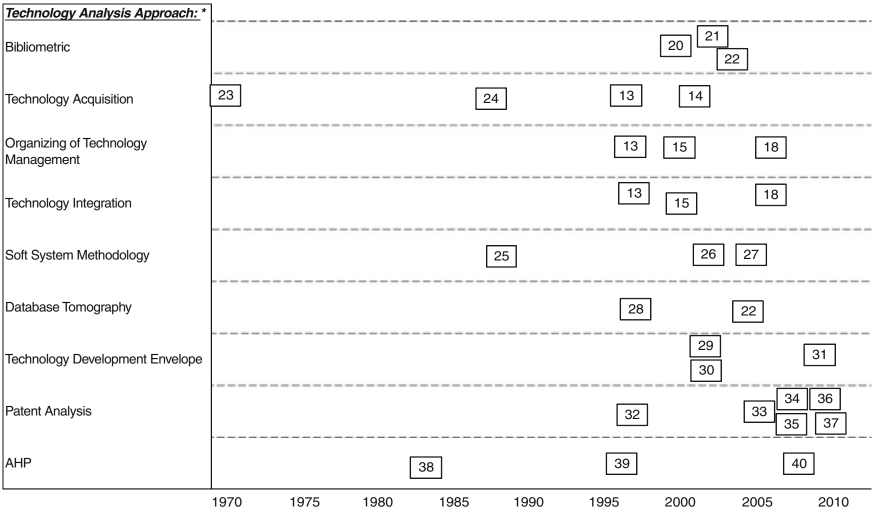


**Fig. 2** Publications on strategic technology planning: technology analysis approach (in order of publication time)

*Database Tomography* (DT) is a patented system for analyzing large amounts of textual computerized material [33, 39]. DT is a textual database analysis system consisting of two major components: (1) algorithms for extracting multi-word phrase frequencies and phrase proximities (physical closeness of the multiword technical phrases) from any type of large textual database (2) interpretative capabilities of the expert human analyst [33].

*Technology Development Envelope* (TDE) method is applied for identifying the optimum path in developing a technology roadmap in which technology strategies and business strategies are combined [40, 41]. The combination of Delphi method and hierarchical decision (AHP) is used as a foundation for building the TDE concept [41, 42].

*Patent analysis*—also known as technology portfolio [28]—could also be implemented in the strategic technology planning on the foundation of technology roadmapping and technology forecasting [43–47]. Yoon [43] and Huang [48] had shown that even though the patent analysis is a powerful technique in technology planning, it is not yet clear whether the analysis is applicable to technology planning—on the foundation of roadmapping and forecasting—over all industries. This condition is a result of different strategies among companies in protecting their innovation. Due to divergence between the use of patents versus. trade secrets according to the characteristics of industries, patent analysis might be inappropriate to some industries.

*Analytical Hierarchy Process* (AHP) is one of the most well known methods in the area of technology planning [42, 49]. AHP is a comprehensive approach to decision making in a complex system. The basic rule in AHP is to decompose

**Table 2** List of author(s) as indicated in Fig. 2

| No | Authors | No | Authors |
|---|---|---|---|
| 13 | Christensen [20] | 29 | Gerdsri [76] |
| 14 | Christensen [25] | 30 | Gerdsri and Kocaoglu [41] |
| 15 | Edler et al. [23] | 31 | Kockan et al. [40] |
| 18 | Grienitz and Ley [26] | 32 | Liu and Shyu [46] |
| 20 | Kostoff and Schaller [31] | 33 | Lee et al. [44] |
| 21 | Kostoff et al. [32] | 34 | Yoon [43] |
| 22 | Kostoff et al. [33] | 35 | Chun et al. (2008) |
| 23 | Jantsch [35] | 36 | Lee et al. [45] |
| 24 | Clarke and Christopher [34] | 37 | Huang and Li [48] |
| 25 | Checkland [37] | 38 | Kocaoglu [50] |
| 26 | Okutsu et al. [38] | 39 | Zhong and Ohsuga [49] |
| 27 | Will [36] | 40 | Gerdsri and Kocaoglu [42] |
| 28 | Kostoff et al. [39] | | |

decision problem into a hierarchy of more easily comprehended sub-problems so each of the sub-problems can be analyzed mathematically and independently [50].

Number in bracket refers to author(s) as listed in Table 2.

## 5 Combined Approaches of Market and Technology

During categorizing all methodologies and approaches in the area of technology planning, we found some other methodologies that are considered to fall into a combination of market and technology approaches. These methodologies include: *change management approach* [51, 52], *synergy making and horizontal technology strategy* [21, 25, 53], *level of acquisition strategy* [20, 21, 23, 25, 54], *technology leakage control* [23], *human resources approach* [27], *scenario planning* [55–58], *cost of innovation* [59], *flexible planning logic* [60], *axiomatic design approach* [61], *innovation matrix* [62], and *technology audit* [63].

*Integrated portfolio*, proposed by Ernst et al. [28], is a combination approach of market and technology portfolio. This approach is developed based on the assumption that pure technology or market portfolios have a one-sided focus on either technology or product market. New technologies have to fulfill market needs to avoid them failing in the market. Integrated portfolio concept is trying to overcome this shortfall by combining market and technology analysis.

Integrated portfolio can be a powerful tool for strategic technology planning purposes because it offers an efficient and effective way to better align market and technology being developed in R&D. Integrated portfolio combines a widely known and used market portfolio concept with a patent portfolio capturing technological aspects [28].

Number in bracket refers to author(s) as listed in Table 3.

**Table 3** List of author(s) as indicated in Fig. 3

| No | Authors | No | Authors |
|---|---|---|---|
| 12 | Hax and Majluf [21] | 44 | Li et al. [56] |
| 13 | Christensen [20] | 45 | Strauss and Radnor [55] |
| 14 | Christensen [25] | 46 | Yamashita et al. [58] |
| 15 | Elder et al. [23] | 47 | Pagani [57] |
| 17 | Pieterse [27] | 48 | Bigwood [59] |
| 19 | Ernst et al. [28] | 49 | Spath and Agostini [60] |
| 40 | Gerdsri and Kocaoglu [42] | 50 | Koc and Mutu [61] |
| 41 | Zhong and Ohsuga [49] | 51 | Groenveld [62] |
| 42 | Lenz [53] | 52 | Martino [63] |
| 43 | Macapanpan [54] | | |

# 6 Analysis and Discussion

## *6.1 Strategic Technology Planning Approaches Before and After the 1980s*

There is a number of interesting facts based on the Figs. 1, 2, 3 to be analyzed. This chapter observed two distinct groups on the approaches of strategic technology planning, before the 1980s and from 1980s until the present. Before the


**Fig. 3** Publications on Strategic Technology Planning: Combined Approaches (in order of publication time)

1980s, the number of publication was much smaller, with the focus of approaches on the market side. Among those approaches, the most widely used was the very well-known method called BCG growth matrix, developed in the early 1970s, which is still applicable to today's business condition. During that era, many companies approached their strategic technology planning with heavy emphasis on marketing side (market pull strategy) as their competitive advantages.

The second group, which is much bigger in quantity, arose and developed in the era of mid 1980s until the present, as shown in Figs. 1, 2 with the focus on both market and technology sides. The technology side gained more attention during this period as shown by the publication number. This is understandable since embedding technology planning—as a part of technology management—into overall business strategy has gained a lot of attention both to academicians and practitioners. There are two major reasons for this phenomenon.

First, since the mid 1980s, the subject area of strategic technology planning has grown a significant interest both for scholars and practitioners as a consequence of rapid technological change. This change has attracted many scholars to explore different approaches, models and methodologies, whether for academic purposes only or industrial application purposes. While on one hand this is a reflection of the richness, diversity and relevance of the field, on the other it demonstrates a comparative conceptual weakness in terms of the lack of a common theoretical base to which all contributions may be referred [64].

Second, the internet was opened to general users in the late 1980s or early 1990s and this new era of information and communication technology has played an important role not only in electronic commerce, but also in the flow of information and data. Accessible online journal database has shortened the time for scholars and business practices to get information to support their research and then modify and implement the knowledge for their own purposes.

This chapter also noted an interesting development occurring during the 1990s in terms of the approaches and methodologies in strategic technology planning. During that era—as shown in Fig. 3—a number of chapters were published with the emphasis to look at the two sides, market and technology and how to integrate them into overall business strategy. Globalization and advanced technology development that took place in the early 1990s reshaped the competitive business environment. In response to these changes, companies were developing new competitive strategies, which in turn require new global organizational structures to be effectively implemented [65]. These conditions had led academicians and practitioners to explore the ideas of how to manage technology that is beneficial for companies and pursue long-term objectives, an idea that has been debated by all major companies. Over the years, all of them have attempted to address these issues through a variety of approaches. Farrukh et al. [66] indicated that companies perceived and implemented strategic technology planning approaches in various ways. However, a company needs to aware that there is a real risk that solutions based on very different theoretical foundations could have a damaging effect on business operations if implemented simultaneously [64].

## 6.2 Focus of Strategic Technology Planning Approaches

Due to the variability in approaches and contents in each methodology identified on strategic technology planning, this chapter categorized them into three predominant categories; (1) market focus analysis; (2) technology focus analysis; and (3) combination of market and technology. Each category had a different perspective based on the business priorities and the development of certain technologies at that time.

Pure technology or market analysis has a one-sided focus on either technology or product market. On one side, new technologies have to fulfill market needs to avoid them failing in the market (market pull). On the other side, new technology can also be pushed into the market to create a new market or expand the market (technology push). The degree of difficulty in balancing and integrating the two approaches will mainly depend on the environment. High-risk environment such as in emerging technology requires a deep understanding on two major factors: the nature of the changing business environment in the medium to long term; and the capabilities of the company.

Technological considerations need to be addressed in formulating strategic technology planning. These considerations include both external factors, such as the nature of technological change and competition level, and internal factors, such as technological capabilities and business priorities. Technology Management Framework, proposed by Probert et al. [64], described how a company needs to formulate strategic technology planning based on two dimensions, market/commercial perspective and technological perspective. The framework talked about how to incorporate strategy, innovation and operation level into both perspectives.

## 6.3 Challenges in Strategic Technology Planning approaches

While many companies are concerned about how to best align technology resources with business objectives (as market/business conditions change, new opportunities arise, and new capabilities are developed), there appears to be little commonality in the approaches adopted to support strategic technology planning, despite of all the techniques that had been mentioned above. Technology planning tends not to be identified as a specific business process, but rather as embedded within other processes, such as a general strategy and planning, innovation, new product introduction and R&D management [25, 66]. Companies face various challenges developing and implementing technology planning into their existing processes and operations.

In terms of strategic technology planning contents, this chapter is able to identify three issues/challenges in the area of technology planning approaches.

As in any other academic chapters, these challenges are an open door for future research to address them.

First, for all the approaches that have been presented in this chapter, little evidence has been found on how well the methodologies and approaches align technology planning with business performance. A technology scorecard could be utilized to align the technology investment of companies with their business performances.

Second, it is worth noting that all of the approaches analyzed in this chapter—especially the combined approaches—build on the foundation of technology roadmapping [3, 15, 25, 31, 32, 38, 39, 41, 42, 52, 56, 62, 66–74]. The process of technology roadmapping is used by a range of companies to support technology strategy and planning [66].

Third, this chapter also found little evidence of an approach or framework that can align between product technology planning and innovation database through the use of the innovation management database as a tool in technology planning.

## 7 Conclusions, Limitations and Future Research

Strategic technology planning is an important activity across any industry or company types, driven by increasing competition, market requirements, regulation, technology change, company strategy and product/service innovation [66, 74]. Strategic technology planning has gained increasing prominence globally. It has been practiced for some time and academicians and practitioners' interest in the technique has recently picked up and evolved through various stages, with shifts in focus and approaches that is considered to give their companies a competitive edge. Many are looking to develop more formal procedures that would smooth the way for the introduction and implementation of strategic technology planning techniques. Of course, technology eventually will find its way into the workplace, with or without planning. However companies that fall back on a reactive, "as needed" approach in their adoption of new technologies runs the risk of making costly, personality-driven choices, rather than tactical decisions that align with their larger corporate strategy and goals [75].

Some of the ongoing research is concentrating technology planning on the foundation of roadmapping with the purpose to align the technology planning with business performance. The main reason for this is that technology roadmapping is considered to reflect 'all the plans (technology and business performance)' and as such build on rather than replace existing techniques in use within a company [66].

There are a number of limitations to this chapter. First, a literature review for the broad category of strategic technology planning tools and approaches is a difficult task, due to the extensive background knowledge needed for studying, classifying, and comparing these publications. Second, this chapter only reviewed journal literature as the primary source of information, thus does not represent the entire body of strategic technology planning literature.

**Table 4** Knowledge gaps and future research opportunities

| Current issues | Knowledge gaps | Research opportunities |
|---|---|---|
| Aligning strategic technology planning (TP) with business performance (BP) | How to build the framework to link TP to BP?<br>How to measure the output? | Utilizing technology scorecard methodology to measure the output |
| TP on the foundation of technology roadmapping (TRM) | How to find the right TRM approach (customize to each industry/company) to achieve the BP? | Using more dynamic approach (dynamic TRM) |
| Linkage between desired product-technology planning and innovation database | Need for improved frameworks and tools, with a desire for simple, structured, robust, flexible and integrated tools and processes | Open innovation as TP tool<br>Innovation database management |

Table 4 describes some potential future research based on the current knowledge gaps that this chapter is able to identify.

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# Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review

**Rimal Abu Taha and Tugrul Daim**

**Abstract** Energy impacts so many aspects of our lives. This makes it necessary to evaluate multiple aspects when we are evaluating energy alternatives. This chapter introduces us to a spectrum of tools for this evaluation.

## 1 Introduction

Energy is a necessity for human beings, but current energy resources are forecast to be limited in the coming years with apparent destructive consequence to the environment. Renewable energy is emerging as a solution for a sustainable, environmentally friendly and long term, cost-effective source of energy for the future. Renewable energy alternatives are capable of replacing conventional sources of energy in most of their applications at competitive long term prices [1, 2]. Selecting the appropriate source of energy in which to invested is a task that involves different factors and policies. Renewable energy decision-making can be viewed as a multiple criteria decision-making problem with correlating criteria and alternatives. This task should take into consideration several conflicting aspects because of the increasing complexity of the social, technological, environmental, and economic factors [3]. Traditional single criteria decision-making approaches cannot handle the complexity of current systems and this problem [4]. Multi-criteria methods provide a flexible tool that is able to handle and bring together a wide range of variables appraised in different ways and thus offer useful assistance to the decision maker in mapping out the problem. As this work demonstrates,

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multi-criteria analysis can provide a technical-scientific decision-making support tool that is able to justify its choices clearly and consistently, especially in the renewable energy sector [5].

## 2 Overview of Multi-Criteria Decision-Making Methods

Multi-criteria decision making (MCDM) is a branch of operation research models and a well known field of decision-making. These methods can handle both quantitative as well as qualitative criteria and analyze conflict in criteria and decision makers [6]. Several classification and categorization exist but in general these methods can be divided into two categories: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) [7]. In MODM, the decision problem is characterized by the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints [8] rather than, as in MADM, the evaluation of a set of alternatives against a set of criteria. MADM is one of the most popular MCDM methods to be adopted to solve problems associated with different perspectives [9]. They contain several different methods of which the most important are Analytic hierarchy process (AHP), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality or more commonly—ELECTRE), and Multi-attribute utility theory (MAUT) [4]. The comparison of MCDM methods related to renewable energy planning is discussed in the literature [6, 10–14]. In a previous analysis by Pohekar et al., multi-attribute utility theory (MAUT) was the most common MCDM method used in energy planning literature, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS) [6].

The main objective of MADM is to select the alternative that has the highest score according to the set of the evaluation criteria. A descriptive summary of the most commonly used multi-criteria decision-making methods is presented below:

- Analytic Hierarchy Process (AHP): A MADM method was first introduced by Saaty [15]. In AHP, the problem is constructed as a hierarchy breaking down the decision top to bottom. The goal is at the top level, criteria and sub-criteria are in middle levels, and the alternatives are at the bottom layer of the hierarchy. Input of experts and decision makers is considered as pair-wise comparison and the best alternative can be selected according to the highest rank between alternatives.
- Analytic Network Process (ANP) : The ANP methodology is a general form of the AHP, both were introduced by Saaty [16, 17]. Although AHP is easy to use and apply, its unidirectional relationship characteristic cannot handle the complexity of many problems. ANP, however, deals with the problem as a network of complex relationships between alternatives and criteria where all the elements can be connected. Cheng and Li an empirical example to illustrate use of ANP [18].

- Preference ranking organization method for enrichment evaluation (PROMETHEE): This method is characterized by ease of use and decreased complexity. It uses the outranking principle to rank the alternatives and performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Up to now, the family of PROMETHEE have included PROMETHEE I & II [19].
- The elimination and choice translating reality (ELECTRE): This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The analysis is focused on the dominance relations between alternatives. It is based on the outranking relations hips and exploitation notions of concordance. The outranking method uses pair-wise comparison between alternatives [13]. The family of ELECTRE includes ELECTRE I, II, III, IV.
- The technique for order preference by similarity to ideal solutions (TOPSIS): The basic concept of this method is that the selected alternative is the one that has the best value for all criteria, i.e. has the shortest distance from the negative ideal solution [20].
- Multi-attribute utility theory (MAUT): This is one of the most popular MSDM methods. The theory takes into consideration the decision maker's preferences in the form of the utility function which is defined over a set of attributes, where the utility of each attribute or criterion doesn't have to be linear [9].

In general, MCDM methods have four basic steps that support making the most efficient, rational decisions: (1) Structure the decision process, alternative selection and criteria formulation (2) Display tradeoff among criteria and determine criteria weights (3) Apply value judgment concerning acceptable tradeoffs and evaluation, and (4) Calculate final aggregation and make decision [6]. There are many discussions in the literature about which MCDM methodology is best to use, and controversy about which is the "right" method applied to a real life problem. Multi-criteria analysis is used to select the "best fitted" solution from multi-attribute distinct options [21].

## 3 Multi-Criteria Decision Analysis in Renewable Energy

Adopting and choosing alternative energy sources is a multidimensional decision making process that involves a number of different characteristics at different levels: economic, technical, social, and environmental [22]. From this point of view, multi-criteria analysis appears to be a suitable tool to merge and analyze all perspectives concerned with the decision making process, by establishing a relationship between all alternatives and factors that influence the decision. It can provide a technical-scientific decision-making support tool that is able to justify its choices clearly and consistently in the renewable energy sector [23]. It is important

**Table 1** Literature Review on MCDM Methods and Application to Renewable Energy Issues

| Application area | AHP/ ANP | ELECTRE | PROMETHEE | Fuzzy sets | Others[a] | Sum |
|---|---|---|---|---|---|---|
| Renewable energy planning and policy | [24–30][b] | [31, 32] | [33, 34] | [31, 35–37] | [3, 4, 12, 38–42] | 23 |
| Renewable energy evaluation | [43–47] | [48, 49] | [19, 50] | [49, 51, 52] | [47, 53–58] | 19 |
| Project selection | [1, 18, 59–62] | [23, 63] | [5, 63–65] | [60, 66–68] | [69–73] | 24 |
| Environmental | [74, 75] | [76] | [76] | | [14, 21, 77–81] | 11 |
| Sum | 20 | 7 | 9 | 11 | 26 | |

[a] Others include: VIKOR, TOPSIS, SWA, SIMUS, UTADIS, value trees
[b] Numbers in brackets refer to reference number

to realize that since there will be conflicting view points and different hypothetical solutions, the "best" choice resulting from applying MCDM methods would be the best negotiated solution, and not explicitly the optimum.

This chapter presents a review of selected literature to analyze and underline the application area and expansion of the most used MCDM methods in renewable energy analysis. Classification of the year, application area, and method used is presented to highlight the trends of research in alternative energy decision-making. After researching the literature, the application area of MCDM in renewable energy was divided into four categories: renewable energy planning and policy, renewable energy evaluation and assessment, technology and project selection, and environmental (Table 1). Renewable energy planning and policy refers to the assessment of a feasible energy plan and/or the diffusion of different renewable energy option. The key factors are: adoption to reach a certain national target, decision factors, national planning, and system indicators. Renewable energy evaluation refers to the assessment of different alternative energies or energy technologies. Choosing between alternatives could be for assessing the "best" energy to be utilized in electrical or thermal energy, or any other systems. Project selection and allocation refers to site selection, technology selection, and decision support in renewable energy harnessing projects. Environmental is concerned with the literature discussing alternative technologies from an environmental perspective and climate issues.

## *3.1 Renewable Energy Planning and Policy*

Selecting between alternative energy sources has usually focused only on cost minimization. It is widely recognized now that energy planning is a much more complicated decision with many actors and factors involved. Pohekar and

Ramachandran presented a review and analysis of several published papers on MCDM and highlighted their applications in the renewable energy area [6]. Wang et al. performed a literature review on MCDM methods used for the selection of energy and its applications to energy issues. The review shows that there are four main criteria categories for the evaluation of energy source and site selection problems: technical, economic, environmental, and social [13].

Georgopoulou et al. utilized MCDM-namely ELECTRE III- to reach a compromise in regional energy problems by analyzing the results and actors' reaction [32]. Beccali et al. developed a case study to illustrate the use of the ELECTRE method and a fuzzy set theory. Both methodologies were applied to the development of a renewable energy diffusion strategic plan. The case study explored advantages and drawbacks of each methodology [31]. Diakoulaki et al. used MCDM to examine the relative contribution of different factors and characteristics in reaching the desired level of energy efficiency and how they can be further exploited in energy policy making [39]. Afgan and Carvalho defined energy system elements and indicators which are used in the analysis and assessment of the relationship between an energy system and its environment. The authors considered five indicators and presented the effect of the priority rating and given weight of each criteria on each selected energy system alternative [3]. Kowalski attempted to combine participatory multi-criteria analysis (PMCA) with scenario building for analyzing energy policy making combined with public and stakeholder inputs [33].

Keeney et al. presented another application of MCDM methods in national energy policy. The authors followed a systematic approach of value trees to come up with a set of criteria that would be used in the assessment of alternative energy systems in Germany [41]. Lee et al. Analyzed the competitiveness of Korea among 30 other nations in hydrogen energy technology development using the analytic hierarchy process (AHP) and two potential scenarios to determine criteria [28]. Lee et al. used AHP and DEA to prioritize energy efficiency technologies in the sector of long-term national energy planning [82].

The main objective of using MCDM is to be able to make more rational and efficient choices to ensure that public values are reflected in decisions. Hobbs and Horn used different MCDM methods to develop a set of recommendations in energy planning and policy through an interview process and several group discussions between stakeholders. The authors discussed the difference between using MCDM for evaluation of criteria and alternatives instead of monetizing all criteria, and concluded that the best approach is a combination of the two methods [12]. Enzensberger et al. emphasized the importance of engaging all stakeholder groups in the criteria evaluation process and explained how considering different view points can help policy planners to anticipate possible problems at an early stage [40].

Renewable energy is foreseen as a sustainable, economically sound alternative to conventional energy resources and can be utilized in many different ways. Köne and Büke in keeping with the sustainability perspective, presented a multi-criteria analysis (ANP) to determine the best alternative technology for electricity generation in Turkey [26]. Zhao et al. utilized an AHP model to evaluate alternative power supply technologies and determine the best option according to the criteria of sustainable development including environmental cost and energy security. The study would help the government of Guangdong Providence to plan for the best power generation technology when expanding the local installed capacity [75]. Topcu and Ulengin dealt with the problem of selecting the most suitable electricity generation alternative for Turkey. They focused on a multi-attribute decision-making evaluation of energy resources and provided an integrated decision aid framework for the selection of the most suitable multi-attribute method for ranking alternatives [34]. Önüt et al. employed analytic network process (ANP) to evaluate the most suitable energy resources for the manufacturing industry in Turkey [29]. Afgan et al. used multi-criteria evaluation in the assessment of different options of conventional hydrogen energy systems and compared them with renewable energy systems [38]. Hamalainen and Karjalainen utilized AHP and value trees to determine the relative weights of the evaluation criteria of Finland's energy policies [24]. Kablan used AHP framework to support management in the prioritization process of energy conservation policy instruments in Jordan [25]. San Cristóbal applied the VIKOR method to the assessment of several renewable energy alternatives in order to select the most fit project for helping the Spanish government to reach the target of 12 % total renewable energy in 2010 [4].

## 3.2 Renewable Energy Evaluation and Assessment

To ensure a sustainable future, the assessment of new energy sources should include all the pillars of sustainability, environmental, economic, and social attributes [83]. Afgan and Carvalho used the sustainability assessment method for the evaluation of quality of selected hybrid energy systems by using analysis of the system composed of different technologies and other selected indicators, such as economic, social, and environmental, as measures of the criteria [53]. Afgan et al. evaluated potential natural gas usage in the energy sector and classified the criteria of the analysis as economic, environmental, social, and technological [54]. Burton and Hubacek investigated a local case study of different scales of renewable energy provision for local government in the UK and compared the perceived social, economic, and environmental cost of small-scale energy technologies to larger-scale alternatives [55]. Chatzimouratidis and Pilavachi assessed different power plant types and compared between traditional and new RE power generating technologies according to the technological, economic and sustainability characteristics. They presented sensitivity analyses by comparing the original criteria weights with four alternative scenarios, changing each criteria weight at each scenario [43, 44]. Roth et al. evaluated the sustainability of current and future power supply technologies in Switzerland and compared available options [58].

When trying to select any alternative energy, conflicts among criteria and stakeholders should be taken into consideration. Haralambopoulos and Polatidis presented a new group decision-making framework of multi-criteria analysis for ranking renewable energy projects. The suggested framework utilized the PROMETHEE II outranking method to achieve group consensus in evaluating renewable energy projects. The proposed framework was applied to data from different scenarios in a case study of exploitation of geothermal energy sources in the island of Chios, Greece [50]. Polatidis and Haralambopoulos presented a new decision-making framework of participatory multi-criteria approach where stakeholders can be engaged in the planning and decision process. The methodology was applied to a number of case studies in Greece in order to evaluate renewable energy options for future investments [57].

Considering the different scenarios for adopting renewable energies would give more insight about the feasibility of such adoption and the conflict in policies or alternatives. Beccali et al. utilized ELECTRE-III to assess an action plan for the selection and diffusion of renewable energy technologies at the regional scale in the island of Sardinia under different scenarios [48]. Cavallaro and Ciraolo applied a multi-criteria method in order to support the selection and evaluation of one or more of the solutions and make a preliminary assessment for the feasibility of installing wind energy turbines in a site on the island of Salina in Italy [56]. Daim et al. utilized MCDA to evaluate the feasibility of two clean power generation technologies, wind and clean burning coal, in the Pacific Northwest [84].

Many researchers applied two or more MCDM methodologies to assess the feasibility of technologies by comparing the results and investigating shortcoming of each alternative. Kahraman et al. utilized two different multi-criteria decision making approaches to select the most appropriate renewable energy in Turkey. Fuzzy axiomatic design (AD) and fuzzy Analytic hierarchy process where applied to the same set of criteria and alternatives and the results from both methodologies were compared [52]. Nigim et al. applied two different MCDM tools to the same set of data for ranking alternative energy of a community in southern Ontario, Canada. The first tool was AHP and the other was Sequential Interactive Model for Urban Sustainability (SIMUS) [45]. Oberschmidt et al. introduced PROMETHEE MCDM method as an applicable approach to comparing alternatives for electricity and heat supply based on a case study of the bio-energy village in Germany [19]. Pilavachi et al. applied AHP methodology to evaluate nine options of electrical generating technologies that use natural gas or hydrogen as fuel [46]. Tzeng et al. compared two methodologies, VIKOR and TOPSIS, to determine the best compromise solution among alternative fuel for buses in Taiwan's urban areas where AHP was applied to determine the relative weights of evaluation criteria [47].

## 3.3 Project Selection and Allocation

One of the main issues recently is adopting renewable energy to ensure a sufficient electricity supply. Expansion of current projects or planning new ones to meet energy demands is a task that involves finding a set of resources and ranking them in an optimal manner. MCDM process can provide a systematic approach to rank alternatives and select the most "suitable" technology. Aragonés-Beltrán et al. applied two multi-criteria decision analysis methods: a hierarchy AHP model and a network-based ANP model, and compared the resulting data to select between different photovoltaic (PV) solar technologies proposed to be invested in a power plant [59]. Begic and Afgan evaluated the options of energy power systems for Bosnia Herzegovina under a multi-criteria sustainability assessment framework in order to investigate options for the selection of new capacity building of this complex system [69]. Cavallaro applied an outranking methodology of MCDA to evaluate different PV technologies according to given criteria for selected in the process of thin film production [5], extended a classic TOPSIS MCDA methodology to the framework of fuzzy-set theory, and used it to compare different heat transfer fluids used in CSP to examine the feasibility of using a new molten salt alternative [67]. The Kaya or Istanbul study, another example, used multi-criteria decision-making analysis to determine the most appropriate RE in Istanbul and the most suitable area to establish it in [60].

Project selection and allocation requires a complex decision-making process that involves a search of the available opportunities and an evaluation of the options by different stakeholders of multiple aspects, both qualitative and quantitative. Aras et al. determined the most convenient location for a wind observation station to be built using analytic hierarchy process (AHP) [1]. Cherni et al. investigated the outcome of applying a new multi-criteria decision support system methodology (SUREDSS) to the case of a rural area in Colombia in calculating the most appropriate energy option for providing power and fulfilling local demand [70]. Goletsis et al. studied energy planning processes to rank the projects and developed a multi-criteria ranking method, a hybrid of ELECTRE-III and PROMETHEE methods. They combined an integrated project ranking methodology for groups with multi-criteria methods in an integrated methodology such as the prioritization of project proposals in the energy sector of Armenia [63]. Project prioritization by Goumas and Lygerou and Goumas et al., extended a multi-criteria method of ranking alternative projects, PROMETHEE, to deal with fuzzy input data. The proposed method was applied for the evaluation and ranking of geothermal energy exploitation projects [64, 72].

Ivanova et al. assessed the feasibility of wind power plant expansion in an electric power system using a hierarchical multi-criteria approach [73]. Lee introduced wind farms and developed the criteria for successful implementation in China, taking into account experts' opinions and stakeholders, input. Lee AHI et al proposed a new multi-criteria decision-making model based on AHP and associated with benefits, opportunities, costs, and risks, to select a suitable wind farm project [61].

### 3.4 Environmental

Different multi-criteria methods have been applied to assess renewable energies from an environmental perspective [44, 75]. MCDM has been increasingly adopted in the area of environmental planning due to the growing awareness of these issues. Zhou et al. provided a survey and literature review and an update of the survey on decision analysis in energy and environmental modeling by Huang [77]. The update showed that the importance of multiple criteria decision-making methods and energy-related environmental studies has almost tripled since 1995 [14, 85]. Greening and Bernow (2004) referred to the potential of MCDM in energy and environmental policy planning [21]. Lahdelma et al. discussed these methods for environmental planning and management [78]. Patlitzianas et al. presented an integrated multi-criteria decision-making approach for assessing the environment of renewable energy producers in the fourteen different member states of the European Union accession [81]. Chatzimouratidis and Pilavachi evaluated different power plants and compared between traditional and new RE power generating technologies according to their sustainability, level and kind of emissions they release using, and impact on the living standard using AHP [43, 44, 74, 86]. Mirasgedis and Diakoulaki compared the external costs of power plants that used different energy sources with a multi-criteria analysis where environmental impacts were expressed in a qualitative scale. They identified similarities and disparities in the obtained rankings and clarified on the basis of the fundamental principles of the two approaches, external cost estimates and multi-criteria analysis [80].

### 3.5 Fuzzy Sets

In many decision-making situations, it is relatively difficult to obtain exact numerical values for the criteria or attributes [51, 87]. Thus, many parameters cannot be evaluated accurately and the data of different subjective criteria and their weights are usually expressed in linguistic terms by the decision maker [36]. In order to overcome this uncertainty in human judgment, fuzzy logic can be applied which deals with vague information by applying membership functions. Fuzzy set theory is integrated to overcome the ambiguity in the preferences. In the literature, different studies had used fuzzy analysis in energy planning and energy policy [31, 35–37, 49, 52, 60, 66–68].

Kahraman and Kaya proposed a fuzzy multi-criteria decision-making methodology which can evaluate linguistic terms, fuzzy numbers, and precise numerical values. The proposed methodology was applied to the case of Turkey to determine the energy policy in the country, by sorting the best available alternatives [36]. Mohanty et al. demonstrated the application of fuzzy set in project selection. The study illustrated an application of fuzzy ANP along with fuzzy cost analysis in selecting R&D projects [68].

### *3.6 Comparison between MCDM Methods*

As shown before, multi-criteria decision-making analysis has been applied to solve many real world problems. Many researchers recently have been interested in comparing two or more MSDM methodologies and analyzing the advantages or drawbacks of each method. Some researchers applied several methods to real life problem data and compared the results obtained from those methods. Theodorou investigated three different MCDM methodologies, namely: AHP, ELECTRE, and PROMETHEE, and their application on energy planning for different subsidy schemes [88]. Chu et al. provided a comparative analysis of Simple Additive Weighting (SAW), TOPSIS and VIKOR, which demonstrated the similarities and differences of these methodologies in achieving group decisions [11]. Hobbs and Meirer compared the methods with respect to simplicity of applications and feasible expected outcomes [89]. Opricovic and Tzeng conducted a comparative analysis of VIKOR and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods using a numerical example to explain their similarities and differences. The authors extended the comparison of VIKOR method with TOPSIS to other MCDM approaches, namely, Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) and ELimination and Choice Expressing REality (ELECTRE), by using a numerical example and compared results of analysis [90, 91].

## 4 Conclusion

In general, evaluating energy systems is a complex analysis that can be defined as a multi-dimensional space of different indicators and objectives. The use of multi-criteria decision analysis (MCDA) techniques provides a reliable methodology to rank alternative renewable energy resources, technologies and projects in the presence of different objectives and limitations. Even with the large number of available MCDA methods, none of them is considered the best for all kinds of decision-making situations. Different methods often produce different results even when applied to the same problem using same data. There is no better or worse method but only a technique that fits better in a certain situation. The current research does not give a clear view about the trend in literature, but can give an insight about the direction it is going. It is noticed that AHP is the most used methodology of all MCDM methods. This can be credited to its simple structure and the ability of an analyst to negotiate results until consistency is achieved, offering near consensus on judgment. The main question that remains is how to choose the appropriate MCDA methodology in alternative energy decision-making.

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# Expert Judgment Quantification

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**Abstract** Expert judgments are used when there are no objective data is available. It is critical to solicit these judgments accurately for decision makers. This chapter reviews methods and issues around the expert judgment quantification.

## 1 Expert Judgment Methods

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 available information [1]. Meyer and Booker describe that expert judgment consists of information and data obtained from the qualified individuals that can be used to solve problem or make decisions in various fields and domains [2]. Keeney and von Winterfeldt describe expert judgement as an expression of opinion, based on knowledge and experience, that experts make in responding to a problem [3]. In the literature expert judgment is also called expert opinion, subjective judgment, expert forecast, best estimate, and educated guess.

The following are some applications of expert judgment [2]:

- Determining probability of an event and assess impact of a change
- Determining present state of knowledge in a field
- Predicting performance of a product or process
- Determining validity of assumptions

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- Selecting input and response variables for a chosen model
- Providing the elements needed for decision making in the presence of several options.

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 [2, 4]. Generally decision making in these situations with high degree of uncertainty about a future environment give rise to two specific needs [5]:

- The need for a methodology to capture the reliable consensus of opinion 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.

Roger Cooke states the following five principles in an attempt to formulate guidelines for obtaining expert judgment [6]:

- Reproducibility: It should be possible to review and if necessary to reproduce all the results.
- Accountability: The source of expert judgment must be identified (not necessarily by name, but certainly by professional background and level of expertise).
- Empirical Control: The results must in principle be susceptible to empirical control.
- Neutrality: The method for combining and evaluating expert opinion should encourage experts to state their true opinions.
- Fairness: All experts should be treated equally.

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 [7]:

- Definition of elicitation objectives
- Identification and selection of the experts
- Preparation of questionnaire, instruments, training session etc.
- Process of obtaining the expert opinion
- Analysis and aggregation of expert judgments
- Synthesis.

There are various means to obtain expert judgment and according to Börjeson et al. usually workshops, Delphi method, and surveys are conducted to obtain expert opinion for the development of scenarios and roadmaps [8]. Technology roadmaps are always developed based upon expert judgment obtained through workshops, expert panels, Delphi studies, and surveys [9]. Therefore, use of expert panels is a widely used approach for technology planning and roadmapping and it has been used in several Ph.D. dissertations [10, 11].

Cooke provides a brief historical overview of expert judgement methods and argues that systematic use of expert judgement for decision making was developed at the RAND Corporation in the United States after World War II [6]. The first two methods using expert judgement, developed by the RAND Corporation, were the Delphi method and Scenario Analysis.

## 2 Scenario Analysis

Herman Kahn is considered as the father of scenario analysis approach and he developed this approach at RAND Corporation [6, 12, 13]. Kahn and Wiener define scenarios *"as hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points"* [14]. Scenario planning has increasingly been applied as a useful tool for the improvement of decision-making process and dealing with uncertainty, by considering number of possible future environments [15]. Scenarios are alternative, plausible and consistent images of the future and highlight the large-scale forces that push the future in different directions [12]. Scenarios are useful whenever the problem is complex, uncertain and has long-term effects [16]. So scenarios significantly enhance the ability to deal with uncertainty and increase the usefulness of overall decision making process [17, 18].

There has been significant growth in the use of scenario planning, especially in the decade up to the year 2010 [17, 19]. Scenario planning has been extensively used at the corporate level, and in many cases it has been applied at the national level [13, 20, 21]. The scenario building process also contributes towards organizational learning [22]. 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 [13, 23, 24]. Scenarios are considered a valuable tool that helps organizations to prepare for possible eventualities, and makes them more flexible and more innovative [25]. Empirical research conducted by Linneman and Klein indicate that after the first oil crisis in the early 1970s, the number of U.S. companies using scenario planning techniques doubled [26, 27].

There are numerous techniques for scenario development ranging from intuitive based approaches to purely quantitative approaches [28]. The literature on scenario planning indicates that scenarios mean different things for different users, and often scenarios are developed for various purposes [8]. On the basis of perspective, scenarios are classified into descriptive and normative scenarios [20]. The descriptive scenarios are extrapolative and the normative scenarios are goal directed. Scenarios are also classified on the basis of scenario topic, breadth of the scenario scope, focus of action, and level of aggregation [16].

Scenario planning approach has been widely used in the energy and renewable energy sector. Scenario planning helps to analyze emerging issues in a complex energy system [29]. It has been applied to forecast energy resources [30], energy foresight and long-term energy planning at the national level [31], analysis of future primary energy demand at national level [32, 33], improvement of energy efficiency and reduction of energy consumption in commercial buildings [34], development of hydrogen energy infrastructure [35–37], deployment [38] and integration of renewable energy [39, 40] and renewable energy portfolio planning [41–44].

## 3 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” [6, 45]. The Delphi method is a popular technique for forecasting and an aid in decision making based on the experts opinions. The need to elicit and synthesize expert opinion inspired the development of the Delphi technique [46]. 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” [47] Delphi is a systematic and interactive method relying heavily on expert panels [48]. Delphi is based upon the principle that judgments and opinions from a structured group of experts are better and more accurate than those from an individual or unstructured group [45, 49]. This method has gained popularity among research managers, policy analysts and corporate planners and has been used extensively in various fields. The Delphi method is applied to technology forecasting and many types of policy analyses in various fields and domains [48].

The Delphi method is based on a structured process for collecting and distilling knowledge from an expert panel through a series of questionnaires combined with controlled opinion feedback. A series of sequential questionnaires or rounds are conducted with controlled feedback in order to gain the consensus of opinion of a group of experts [47]. Feedback and opinion of group members is summarized, combined and given back to experts after the first Delphi round and they are asked the same questions again [47, 48]. This process is repeated until a general consensus in the outcome is obtained or results are stabilized. Research on number of Delphi rounds indicates that of the most changes occur in the transition from the first to the second round when members of expert panel change their judgment and generally four rounds are sufficient to reach consensus [50]. This systematic control ensures objectivity to the outcome of a Delphi study and provides a sharing of responsibility which releases the participants from group inhibition [51].

The Delphi Method also reduces the impact of the powerful members in the group by establishing anonymous group communication and avoids imposition of their point of views on other group members [47]. Torrance state that power or status of the group members influences the decisions and less powerful members demonstrate an unwillingness to disagree with the most powerful member, even if they have the correct solution and this may adversely affect quality of the decisions [52]. Moreover, in highly structured cultures individuals may refrain from expressing their opinions freely, so Delphi can be used as a useful approach to overcome cultural barriers [11]. The Delphi method is also used as a useful communication tool to generate a debate [53]. The following three characteristics of Delphi method distinguish it from conventional face to face interaction [48, 49, 54]:

- Anonymity: Each expert gives his answers to the questions in an independent and anonymous way without any undue social pressures and 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. Iteration allows the experts to change their opinions. Controlled feedback takes place after every Delphi round, during which each group member is informed of the opinions of the other group members. Thus, participants are encouraged to review their answers in light of the combined judgment of all participants.
- 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. It includes statistical information of the group response such as the mean or median and the extent of the spread of members' opinions.

In the first Delphi round, members of the expert panel are asked questions related to the subject matter under consideration. 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 justification of their rationale if they differ from the majority judgment. Due to controlled feedback from the previous rounds, sometimes experts tend to achieve a consensus of opinion [55]. However, this process is iterated until consensus is generated or results are stabilized between two rounds. Linstone and Turoff emphasize that the number of rounds should be based on when stability in the responses is attained, not when consensus is achieved [56]. Chi squared test has been proposed in the literature to determine the stability of results from an expert panel [57].

The Delphi method has undergone substantial evolution and diversification. Online Delphi approach can play an important role and allows conducting study in shorter time period, ensuring anonymous contributions, summarizing results quickly, and has been used in multiple applications [58–60]. Linstone and Turoff state that in future Delphi will be used as an online tool [56]. In this approach Delphi panelists have access to a web-based questionnaire. Use of computers and internet have enhanced the original concept and make it possible for any group member to participate from anywhere in the world [58]. Geist made a comparison of traditional paper–pencil version of the Delphi method with web-based, computerized, and real-time version and described that web-based Delphi can overcome some shortcomings of the traditional approach [61]. Literature review also suggests some variants of the Delphi technique based on the purpose of the project like the classical Delphi, the policy Delphi and the decision Delphi [62, 63].

## 3.1 Advantages of the Delphi Method

The Delphi method helps to achieve consensus in a given area of uncertainty or lack of empirical evidence [64, 65]. Participants of a Delphi study bring their extensive knowledge and vast experience to the decision making process [65]. The Delphi technique is very useful in situations where individual judgments must be tapped and combined to overcome incomplete state of knowledge [64]. The controlled feedback between the Delphi rounds stimulate new ideas and it is also motivating for the participants [66].

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 [56]. Absence of an obligation to meet in person improves the feasibility of the Delphi, significantly lowers its cost [67], and allows participation from diverse geographic locations.

Rowe et al. suggest that the structured approach and participant anonymity offered by Delphi approach leads to a process gain [49]. 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 powerful individuals [55, 65]. In face to face interactive groups there is a tendency among low-status members to "go along" with the opinions of high-status members despite of contrary feelings [52]. In contrast, the Delphi method can overcome these negative effects and in a Delphi study consensus reflects a normative rather than informational influence or tendency to follow the leader [65].

Brockhoff, Riggs, Larreche and Moinpour found that a Delphi procedure produces superior predictions and accurate forecasts than a normal interacting group or a face-to-face committee meeting [68–70]. Rowe and Wright also systematically reviewed the empirical studies looking at the effectiveness of the Delphi technique and found that the Delphi method outperforms other structured group procedures by providing more accurate assessments or judgments [45].

The Delphi technique is also very useful in situations when there no adequate models exists to develop a statistical prediction and Coates says that Delphi is the last resort in these situations [71].

## 3.2 Disadvantages of the Delphi Method

It takes long time to conduct a Delphi study due to nature of the process [55] and extensive time commitment is required.

Output of a Delphi process reflects the best opinion of the experts [66] so it is critical to choose appropriate experts. Sometimes selection of expert panel is problematic.

It is possible that in pursuing the consensus among experts 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 [72].

It is also argued that anonymity in a Delphi study may lead to lack of accountability of views expressed and encourage hasty decisions [72]. However, the sequential Delphi processes may positively discourage such action.

Sackman points out in his critical review of the Delphi method that it is difficult to determine reliability and scientific validation of the findings [72]. It is because 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 [66].

### *3.3 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 [47]. Martino states that it remains one of the most popular methods for technology forecasting [73]. Delphi is considered a promising technique in future roadmapping [10, 74] and scenario planning activities [31, 75, 76]. The literature review highlights widespread use of the Delphi method for 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 [21, 31, 47, 53, 74, 77, 78]. Delphi method has been a useful tool for solving problems in energy sector for developing energy roadmaps and energy foresight projects [31, 79–86].

Delphi method has also been used by many countries; there are examples of various Delphi studies conducted at national level in Germany [87], Japan [74, 88], France [83], Turkey [89], Thailand [90], India [91], Poland [31], Finland [82], Korea [92] and Austria [93].

## 4 Multi Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) methods are considered an appropriate and useful decision making tool for multi-dimensional, intricate and complex decision problems. MCDA is also suitable for conflicting evaluations consisting of multiple aspects and helps the decision makers to find a way to make rational compromises. MCDA methodology requires identification of criteria, sub-criteria, and alternatives related to a goal, followed by assigning numerical measures to evaluate importance of criteria and sub-criteria and finally the alternatives are prioritized and ranked [94]. Experts are used to assign these numerical measures in order to prioritize the available options [95]. There are many MCDA methods highlighted in the literature including: Analytical Hierarchy Process (AHP), Multi-Attribute Global Inference of Quality (MAGIQ), Goal Programming, Simple Multi-Attribute Rating Technique (SMART), SWING, SIMOS and Technique for order preference by similarity to ideal solution (TOPSIS), Preference ratios in multi-attribute evaluation (PRIME), weighted sum and weighted product methods etc. [94, 96, 97]. Wang et al. conducted a detailed literature review and thorough analysis of various MCDA methods and concluded that AHP is the most popular and comprehensive MCDA technique [96].

Analytic hierarchy process (AHP) is a widely used MCDA method and considered a very effective and powerful technique. AHP approach was developed by Thomas L. Saaty in the 1970 s and it has been used by decision-makers in diverse applications to resolve decision problems. It is a paired comparisons technique. International scientific community has accepted AHP as a robust and flexible decision making technique, useful for complex decision problems [98]. AHP is primarily used for the resolution of choice problems in a multi-criteria environment [99]. AHP technique allows decision maker to decompose the complex decision problem in a logical manner into many small but related sub-problems in the form of levels of a hierarchy [100]. AHP technique also allows the decision makers to incorporate both quantitative and qualitative judgments into a decision problem [101]. Evaluation of weighting and scoring can be objective if actual data is available related to criteria and alternatives; otherwise subjective data (expert judgment) obtained by pairwise comparisons through expert panel is used.

In general, AHP methodology provides a comprehensive and rational framework for structuring a decision problem. AHP technique has the following three fundamental concepts [100]:

- Structure complex decision problem as a hierarchy of goal, criteria, sub-criteria and alternatives, with goal at the top of the hierarchy, criteria and sub-criteria at lower levels and alternatives at the bottom of the hierarchy
- Pair-wise comparison of elements (criteria and alternatives) at each level of the AHP model with respect to each criterion on the preceding level. Through pairwise comparison the ratio-scaled importance of each alternative is calculated
- Synthesizing the judgments over the different levels of the hierarchy.

Pairwise comparisons are used to prioritize and rank the criteria and alternatives for decision making. Satty recommends to use 1–9 scale measurements and eigenvector approach [100]. In contrast to this Kocaoglu recommends constant sum approach by allocating 100 points between each pair [102]. Constant sum method using 100 points is considered better than 1-9 scale measurements approach because user can state their judgments without limiting to nine point scale [11]. Through these three steps, AHP technique estimates the impact of each alternative on the overall mission or goal of the decision hierarchy. This approach also helps the decision-makers to compare conflicting criteria and subsequently prioritize and rank the alternatives.

AHP method employs a consistency test to screen out inconsistent judgments by any expert and this is also considered as an advantage of using AHP. It is important that the decision-makers should be consistent in their preference ratings expressed by pairwise comparisons. Saaty recommended that consistency ratio (CR) should be less than 0.10 and mentioned that CR greater than 0.10 indicates serious inconsistencies and in that case AHP may not provide meaningful results [100].

### *4.1 Application*

AHP has been extensively applied to a wide variety of decision problems in various domains including project selection and evaluation, measuring business performance, technology evaluation and selection, technology policy, energy policy, new product screening, portfolio management, customer requirement structuring, arms control, transport systems, agriculture sector, real estate investment, conflict resolution, quality management, public policy, and healthcare [90, 94, 98, 99, 101, 103, 104]. In the energy sector especially for renewable energy technologies, AHP approach has been used for energy policy formulation, energy planning, power plant selection, power plant site selection, prioritizing emerging renewable energy technologies, energy resource allocation, energy resource assessment, integrated resource planning, renewable energy exploitation, controlling greenhouse gas (GHG) emissions, energy conservation, and developing energy management systems [94, 98, 103, 105–121].

## 5 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 foresight studies and based on the use of expert knowledge are mentioned in this section.

### *5.1 Nominal Group Technique*

Delbecq and Van deVen developed the Nominal Group Technique (NGT) in 1968 and it is a structured decision making method for working toward consensus [64]. 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 [64, 122]. Its major strength is that opinions of everyone are taken into account, so every team member has an equal voice in sharing ideas. During the ranking process, the duplicate solutions are eliminated and every participant ranks the ideas as 1st, 2nd, 3rd, 4th, and so on. This 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.

NGT has gained considerable recognition and it has been widely applied in health, social services, education, industry, and government organizations [123]. The NGT process consists of the following six steps after defining the problem [64, 123]:

- 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 or rating followed by group discussion and group decision.

NGT is a useful approach especially in the following situations [64, 122, 123]:

- When 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 participate due to apprehension of being criticized or any other reason
- When group members think better in silence
- When some group members are new and less experienced than others or there is difference in their social status like manager and staff
- When the issue is controversial or there is heated conflict
- When it is desired to generate a lot of ideas
- When it is required to prioritize a few alternatives for further examination.

Major advantage of NGT is that it provides balanced participation of every member of the expert panel in the process and final result. NGT groups perform better than other interacting groups in accuracy and better use of group resources because all members participate and it results in better decisions [124]. 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.

Major disadvantage of NGT is that it is overly mechanical, simplified and lacks flexibility. It is focused on a single purpose and single topic. Only individual brainstorming is done and cross-fertilization of ideas is constrained. 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 reasons, it has been recommended to combine NGT with other group techniques to overcome these limitations [125].

### 5.2 Focus Groups

Focus groups are generally used for idea generation [126]. In this technique a group of experts focus on a topic and they are asked about their views, perceptions, opinions, beliefs and attitudes towards a product, service, concept, idea or advertisement [126]. Questions are asked in an interactive group setting and the experts are free to talk with other group members in an open environment. Generally 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 [122].

### 5.3 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 [127]. Its main objective is to elicit ideas from a group of people [128]. Brainstorming brings new ideas on how to tackle a particular problem in a freethinking atmosphere and presents a wide range of ideas and solutions. Participants are encouraged to freely articulate their ideas followed by more rigorous discussion in order to stimulate creativity and thinking "out of the box", to let dissident viewpoints enter into discussion at an early stage [128]. Brainstorming technique also supports the future studies but does not produce an actual technology forecast. Effective brainstorming sessions consists of 7–12 participants.

### 5.4 Mindmapping

This technique is also sometimes used in foresight with the brainstorming and other group discussion methods [128]. Experts are asked about the relationships between a large number of factors and highlight the forces driving or shaping a course of development. It allows for a quick charting of a group's ideas into logical groupings and connections between them. Mindmapping technique can be used in the course of brainstorming for ideas, and can help establish a skeletal framework. Its output is typically a chart or set of charts, outlining key issues and the linkages between them; and this can be used for communication purposes, scenario construction, or in many other ways [128].

## 6 Expert Judgment Methods used in Nuclear Studies

The following expert judgment methods are developed and mainly used in studies related to nuclear power plants to assess safety of nuclear power plants, facilitate the safety related decision making, and get estimates of subjective probabilities for unknown parameters and uncertain events [129–131]. Cojazzi et al. analyzed these expert judgment methods in a benchmark exercise [130], and these are summarized in Table 1.

- NUREG
- KEEJAM
- STUK-VTT
- CTN-UPM
- GRS
- NNC
- SEJ-TUD.

Although these expert judgment methods presnted in Table 1 are very structured but these are developed and used to study nuclear safety issues. These methods are commonly used in technology foresight studies.

## 7 Formation of Expert Panel and Selecting the Experts

It is very important to carefully select the members of the expert panel because the quality of all expert judgment is directly based upon their knowledge, capability, and experience. Expert judgment is used to forecast the future utilizing information derived from individuals who have extraordinary familiarity with the subject under consideration [122]. An expert is a person who has the background and knowledge in the subject area and considered qualified to answer the questions [2]. Usually questions are posed on the experts when they cannot be answered by any other means. Members of an expert panel should reflect current knowledge and perception as well as they should be impartial to the research findings [55].

The literature also highlights that well known experts should be selected who are respected among their peers and careful selection of experts increases credibility to the project [132]. Camerer and Johnson describe that an expert is considered an experienced person having some professional or social credentials and know a great deal about their domain [133]. McGraw and Haribson-Briggs state that domain experience, commitment, patience, persistence, ability to communicate ideas and concepts, introspective of own knowledge, honesty, and willingness to prepare for session are the important personal characteristics of the experts [134]. Landeta highlights that selection of suitable experts help to achieve reliability of the study [135]. 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

**Table 1** Formal expert judgment methods [129–131]

| Expert judgement technique | Developed by | Characteristics |
|---|---|---|
| NUREG | Nuclear Regulatory Commission (NRC), USA 1987–1990 | NUREG is a highly structured method used to evaluate the state of knowledge of events, variables or processes, when there is incomplete data or inadequate models. It includes training of the experts, review discussions, individual elicitations, composition and aggregation of the opinions and review by experts<br>In this approach, the domain experts write reports on the issue and their final estimates are elicited individually after expert's discussions and then averaged on equal weight basis |
| KEEJAM | Joint Research Center (JRC)—European Commission and Italian Universities in 1997 | It is knowledge based method and employs Knowledge Engineering techniques. It includes explicit modeling of the knowledge and problem solving procedure of the domain expert<br>This approach provides structured and disciplined support to the knowledge engineer in eliciting the knowledge and reasoning strategies of the experts, building consistent knowledge models, and applying these models to the solution of expert judgement task |
| CTN-UMP | University of Polytechnics, Madrid, Spain in 1997 | This method is developed on the basis of the NUREG Method. It estimates subjective probabilities for unknown parameter and uncertain events and consists of nine steps. Its main difference from NUREG Method is regarding the way to aggregate evaluation of the experts. |
| GRS | Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany in 1985 | This Method has been developed to quantify the state of knowledge in elements of a decomposition of the question and to propagate it though this decomposition in order to arrive at a quantitative uncertainty statement for the answer. It aggregates the judgments at lower levels and propagates them through the decomposition to arrive at a quantitative expression of the resulting state of knowledge at the model output level |

(continued)

**Table 1** (continued)

| Expert judgement technique | Developed by | Characteristics |
|---|---|---|
| STUK-VTT | STUK Radiation and Nuclear Safety Authority), Finland in 1997 | The method is originally developed for quantitative risk or reliability assessments in engineering and economical analyses, where remarkable uncertainties are present<br>The method is based on probabilistic representation of uncertainties. The predictions obtained from experts are expressed as probability distributions. Then, the combination of these assessments is based on hierarchical Bayes model. Due to this property, it is also possible to deal with experts who are not familiar with the concepts of probability |
| NNC | UK, 1996 | NNC is a quality based method, leaning on quality assurance methods and problem solving processes; this approach is based on individual estimates. It involves a multi-disciplinary team, defined as a set of individuals with different but complementary skills |
| SEJ-TUD | Delft University of Technology, The Netherlands in 2000 | This is a European Guide for expert judgment in uncertainty analysis. It deals with procedures to perform an expert judgment study with the aim of achieving uncertainty distributions for an uncertainty analysis. This method consists of 15 steps |

judgment [49]. Quality and validity of the elicitation process is further improved when the experts feel that they are knowledgeable and well-informed [136].

In the context of scenario planning, van der Heijden state that experts are remarkable people who have some knowledge of the related field or industry, and are acute observers of the environment [18]. Scenarios expert panel members are expected to be fairly knowledgeable of the socio-economic contexts of the region [128]. Schaller highlights the importance of competent experts to ensure quality of technology roadmaps [137]. More qualitative approach has to put a strong emphasis on the selection of suitable experts [16]. 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.

Shanteau describes the following important characteristics of an expert [138]:

- Extensive and up-to-date knowledge
- Good perceptual abilities so that the expert can extract information and make good judgment
- Ability to sense what is irrelevant when making decisions
- Ability to simplify complex problems
- Ability to clearly communicate their expertise and persuade others
- Strong sense of responsibility and a willingness to stand behind their recommendations
- Ability to work under stressful conditions
- Ability to propose creative solutions to the decision problems
- Exhibit self-confidence in their decision making.

Usually the experts with different backgrounds are brought into 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 [132]. 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 [65]. In support of this argument, Rowe and Wright suggest that diverse background of the experts brings diversity to a panel [45], and group situations may inhibit creativity and bring possibility of resolving ambiguous and conflicting issues [49]. Members of the expert panel bring their knowledge and experience to the decision making processes [65]. Linstone and Turoff suggest that diversity of viewpoints will help to generate interest and involvement among the participants of an expert panel [47]. Diversity of experts' experience is considered as an important asset to the success of a research project [128]. In addition to technical qualifications and expertise, the expert panel members should be creative thinkers, who can bring diverse viewpoints, work well in groups, and freely express their views and opinions [128].

Delbecq et al. cite that heterogeneous groups consisting of participants with widely varying personalities and different perspectives on an issue, produce acceptable solutions of higher quality than homogeneous groups [64]. Diverse backgrounds of expert panel members also help to assure that any bias from any member would have little impact on the overall outcome of the study [11]. Gathering diverse experts in the panel will minimize the influence of a single individual. Moreover, in order to avoid biases that may be caused by personal influence, it is recommended that members in the panel are not given information about the other members [11]. Ascher state that there is a human tendency to stick with the status-quo and not to look outside their comfort zone when considering the future and utilization of multiple experts with different viewpoint helps to overcome this human tendency [139]. Thus, diversity among the members of an expert panel plays a vital role and a group of diverse experts will lead to better quality of the judgment [132, 139].

It is critical to have appropriate number of experts in an expert panel. Mitchell state that the expert panel must have at least 8–10 members [140]. Whereas, Meyer and Booker recommend to have around five to nine experts in a panel and state that having less than five experts in a panel will reduce the chances of providing adequate diversity of information to make credible inferences [132]. Some researchers suggest that more participants are better because their combined opinions will increase the reliability of composite judgment [65]. However, large number of participants in an expert panel will result in difficulties to coordinate with them and analyze their feedback. Therefore, it is important to balance the size of the group appropriately. Research indicates that for Delphi studies a group of 11–15 experts is preferred for achieving high correlation [48, 64, 141]. It has been empirically proved that panel reliability increases with increase in panel size and 11–15 is considered an optimum size of an expert panel [48]. In a widely cited article 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 [53]. The number of experts also depends on the scope of the problem, objective of the study, and resources available [64, 132] and sometimes a larger group may be useful if the study seeks to increase group support or understanding rather than decision making or gaining information.

Issues related to logistics are also important concerns for the selection of experts such as: willingness of expert to join the panel, willingness to devote their time for the study, and permission from their employer to participate in the research [132]. It is very important that expert panel members are willing and able to make a useful contribution [47, 53]. 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 experts and formation of the expert panels [49, 142–144]

- 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 panel members
- 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 [132]. Therefore, it is important to select a balance group of experts from the government, universities, research institutes, regulatory agencies, and various segments of industry. It will ensure that members in the expert panel have diverse backgrounds and they cover all segments of an industry or sector.

# 8 Inconsistencies in Expert Judgments

Consistency is the degree to which an individual is consistent in his/her own judgment. Inconsistency describes a situation where expert judgments change over time. In this section it is described how to verify consistency of responses obtained from a group of experts and consistency of responses of individual expert.

## *8.1 Consistency of Expert Panel*

Consistency of responses between successive rounds of a Delphi study is also referred as stability [57, 145]. If most members in an expert panel choose the same reply in two consecutive rounds then it is considered that consistency or stability has been achieved. Kastein et al. state that consistency of responses of panelists over consecutive Delphi rounds reflects high reliability [146]. Dajani, Sincoff, and Talley recommend to conduct Chi square ($\chi^2$) test to measure whether stability of group response has been achieved or not. Responses of two successive rounds obtained from a group of experts are required to conduct this test. The following two hypotheses are tested to determine whether Delphi rounds and response categories are independent [145]:

$H_0$: The Delphi rounds are independent of the responses obtained in them.
$H_1$: The Delphi rounds are not independent of the responses obtained in them.

If the null hypothesis ($H_0$) is supported by an appropriate statistical test, it can be concluded that there is no dependency relationship between round and responses. If, on the other hand, the alternative hypothesis ($H_1$) is found to be true, a dependency could be concluded and the response frequencies between rounds could be construed as different. If the null hypothesis is found to be true, it indicates that group stability has been achieved between the Delphi rounds, and the study may be terminated. However, if $H_1$ is found to be true then we conclude the opposite and it is required to pursue the study in further rounds.

In order to conduct Chi square ($\chi^2$) the observed and expected frequencies of occurrence of particular types of responses in each of the two rounds being tested must be determined first. The required Chi square statistic for testing the above hypotheses can then be calculated from the following Eq. 1 [145]:

$$\chi^2 = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{1}$$

where,

$O_{ij}$ Observed frequency for response interval j in round $i$

$E_{ij}$ Expected frequency for response interval j in round $i + 1$

$i$ Delphi round $i$

$j$ Response interval $j$

The observed frequencies are readily available from the raw Delphi data, and the expected frequencies are determined under the assumption that the null hypothesis is true. So the expected frequency that would occur in each cell if the null hypothesis was true would be the average of the two frequencies observed in the two consecutive rounds.

## *8.2 Consistency of Individual Expert*

Chaffin and Talley argue that it is more important to establish individual consistency than determining group consistency [57]. They extended the work done by Dajani et al. and empirically demonstrated that individual stability does imply group stability; whereas, group stability does not necessarily imply individual stability [57]. So Chaffin and Talley proved that the individual stability test provides more information than the group stability test for measuring consistency of responses between successive rounds of a Delphi study and recommended to use individual stability test whenever possible. They refer stability to the consistency of responses between successive rounds of a Delphi study [57]. The Eq. 2 is used to calculate individual stability in two consecutive Delphi rounds [57]:

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

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 test individual stability in Delphi studies, we need to determine whether there is a significant difference between individual responses in two consecutive rounds using the same Chi square test. The following hypotheses are tested again:

$H_0$ Individual responses of rounds $i$ and $i + 1$ are independent.
$H_1$ Individual responses of rounds $i$ and $i + 1$ are not independent.

### *8.3 Index of Individual Stability*

Chaffin and Talley also suggest to use the "index of predictive association" to measure the extent of individual stability between two consecutive Delphi rounds [57]. The index of predictive association is first proposed by Guttman and later on further developed by Goodman and Kruskal, so it is also called Goodman–Kruskal index of predictive association [147]. It is used to measure the extent of association between two attributes. In case of expert judgment it is used to measure the ability to predict response of round $i + 1$ from those of the $i$th round. The index gives the proportional reduction in the probability of error in predicting the responses of round $i + 1$ given that the responses of the $i$th round have been specified. Chaffin and Talley further state that if value of the index is zero; then there is no predictive association and if the index is 1.00, there is complete predictive association [57].

The Eq. 3 is proposed to measure the degree of individual stability between two consecutive Delphi rounds [57]:

$$\mathrm{I} = \frac{\sum max\ O_{jk} - max\ O_{.k}}{n - max\ O_{.k}} \tag{3}$$

where,

$O_{jk}$ Number (or frequency) 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 $i + 1$
$max\ O_{jk}$ Largest frequency for the $j$th response interval at the $i$th round
$max\ O$ Largest total frequency among the $k$th response intervals at round $i + 1$
$n$ total observed frequencies

A high value of index indicates that there is relatively high predictive association and individual stability has been achieved. If the value of index is 0, then there is no predictive association. Its value range between 0 and 1.

Thus, it is concluded that Chi square test indicates stability, but does not indicate about the degree or extent of association; whereas, the index of predictive association also measures the degree of association (or consistency) and it can provide a valuable adjunct to the Chi square test.

## 9 Disagreement Among Experts

Disagreement is the extent to which members in an expert panel are in difference to each other in their judgments. There is a misperception and some people assume that experts will always reach same the conclusion if they are given the same data and if the experts conclude differently, they consider that judgment is questionable [2]. However, this concept is misleading for expert judgment due to two reasons [2]. First reason is that experts do not possess the same knowledge even if they possess same background information and data of a problem. Due to different background and professional experience each expert differs in their expertise and knowledge. If we assume that experts have same knowledge even then they will use it in different ways and may come up with different judgment. Second reason is that usually expert judgment is obtained in uncertain situations, where no clear standards or well developed theories exist. Therefore, the expert judgment may leads to some disagreement among their opinions.

The experts may disagree because they think differently about a problem especially when confronted with a multidisciplinary problem having scientific complexity and uncertainty, it is quite possible that competent, honest and disinterested experts may arrive at different conclusions [148]. Difference among the expert brings different perspectives on the problem under consideration and research indicates that combining different answers from the experts brings better chance of covering the right solution [2].

Torrance argues that the more effective groups are characterized by greater participation and wider divergence of expressed judgment [52]. Disagreement within the group will increase the range of judgments considered in making a decision which increases the accuracy of decisions [52]. Shanteau state that sometime due to disagreements, the experts increase their understanding of the subject [138].

Mumpower and Stewart describe that the following factors may cause differences in expert judgment [148]:

- Different problem definitions
- Poor quality or missing feedback

- Poor quality, missing, or different information available
- Causal texture of the environment.

In Delphi study, difference of opinions also occurs due to level of expertise, selection procedure of respondents, clarity of questions, complexity of issue under consideration, and criteria for iteration [57, 145].

## 9.1 Levels of Agreement

Dajani, Sincoff and Talley state five levels of agreement in Delphi studies: consensus, majority, bipolarity, plurality, and disagreement, and these level are explained in Table 2 [145]:

It is recommended to terminate the study when the consensus or majority is achieved with stability [145]. 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 and stability is established, 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 as to whether to terminate or rephrase the question statement [145].

## 9.2 Measure of Disagreement

Graham, Regehr and Wright propose to use Cronbach's alpha (α) to measure and determine consensus among members of an expert panel [67]. They define the concept of consensus within a group of experts as a condition of homogeneity or consistency of opinion among the panelists [67]. Cronbach's alpha is a statistical index used to quantify the reliability of a summation of entities which are panelists

**Table 2** Levels of agreement in Delphi studies [145]

| Levels of agreement | Description | Example (in a Delphi study with 20 participants) |
|---|---|---|
| Consensus | Occurs when unanimity is achieved concerning any given issue | Unanimity among all 20 participants |
| Majority | Occurs when more than 50 % of the respondents exhibit consistency | With 11–19 participants responding the same |
| Bipolarity | Bipolarity occurs when respondents are equally divided over an issue | With a 10–10 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 9 |
| Disagreement | Occurs when each respondent maintain views independent of each other | Every respondent in a different subgroup |

in this case [149]. Cronbach's alpha is usually used to measure internal consistency and its value varies between 0 and 1. Its value in the range of 0.7–0.8 are considered satisfactory, indicating acceptable level of consensus among the experts [149]. However, for the clinical applications, much higher value of Cronbach's alpha is desired and 0.90 or greater value is considered appropriate [67, 149]. Thus, a higher value of Cronbach's alpha, closer to 1 suggests consensus and agreement in the expert panel. Graham, Regehr and Wright argue that Cronbach's alpha is a better measure than the Spearman-Brown formula [67]. Cronbach's alpha estimates the reliability of the sum of panelists responses using the Eq. 4 [67, 149]:

$$\alpha = \left(\frac{k}{k-1}\right)\left(1 - \frac{\sum \sigma_{yi}^2}{\sigma_x^2}\right) \tag{4}$$

where,

$K$ number of panelists

$\sigma_{yi}^2$ The variances of each individual panelist responses

$\sigma_x^2$ The variance of the sum of responses for each individual panelist.

Graham et al. further state that the Cronbach's alpha is used to measure agreement and consensus among the Delphi panelists [67].

In a Delphi study involving 456 experts, Celiktas and Kocar used standard deviation to measure the variability or dispersion of expert judgment of the participants [59]. A low standard deviation indicates that the data points tend to be very close to the same value (the mean), while a high standard deviation indicates that the data are spread out over a large range of values. Thus, it is an appropriate approach for large number of experts.

In another Delphi study Terrados, Almonacid, and Pérez-Higueras recommended to use Variation Factor ($v$) in order to gauge disagreement and it can be calculated using Eq. 5 [150]:

$$\text{Variation Factor} = v = \frac{\sigma}{\mu} \tag{5}$$

where, $\sigma$ is the sample standard deviation and $\mu$ is the sample arithmetic mean. In their study, Terrados et al. found that the consensus among the experts increased in the second Delphi round and value of variation factor decreased [150].

Kastein et al. used the intraclass correlation coefficient (ICC) to evaluate reliability of a Delphi project conducted to develop evaluation criteria for the performance of family physicians in the Netherlands [146]. They state that reliability of Delphi can be evaluated in a more accurate and effective way by means of ICC when numerical ratings of respondents are available and these ratings are normally distributed [146]. ICC quantifies the reliability of the results of an instrument, its value varies between 0 and 1 indicating degree of agreement among the experts and higher value indicates a higher level of agreement among the experts [151, 152].

### 9.3 Reducing Disagreement Among Delphi Participants

There is a crucial difference between Delphi and a traditional panel, where consensus is desired and may even be forced in some cases [56]. Coates emphasizes that "*the Delphi is not in reporting high reliability consensus data, but rather in alerting the participants to the complexity of issues, by forcing, cajoling, urging, luring them to think, by having them challenge their assumptions*" [153].

It has been observed that greater concern is given toward agreement among the experts in studies related to healthcare, medical diagnostics, and risk and safety assessment. However, for scenario development, technology foresight, and technology roadmapping it is encouraged to have diverse input from the experts. 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 this variety and contribute to shape the desired outcome.

Rohrbaugh describes feedback of outcome after every Delphi round is the compelling force toward reducing the disagreement among a group of experts [1]. Kastein et al. recommend that through a standardized expert selection process, group size, background information, proper design of the questionnaires, and the provision of feedback; disagreement can be reduced among the experts [146]. Thus, through careful selection of the expert panel members, providing adequate background information, making clear questionnaires without any ambiguity, conducting multiple rounds, and giving proper feedback can significantly reduce the disagreement among the experts.

### 9.4 Disagreement Among FCM Expert Panel

Sometimes causal maps and Fuzzy Cognitive Maps (FCM) are created for scenario planning. There are certain techniques to measure disagreement among the members of FCM expert panel. Multiple FCMs can be combined together to develop an integrated FCM. The integrated FCM captures and summarizes the judgment of all expert panel members in one map for further analysis [154]. The combined FCM is considered stronger and robust than an individual FCM because it possess information obtained from multiplicity of sources [155].

During this process of obtaining causal maps from multiple experts, it is quite possible that experts will differ in content of the map, weight or direction of causal link when addressing the same problem. Taber and Siegel proposed a method to combine multiple FCMs based on calculating the expert credibility weights of every expert. They conducted a study to explore the estimation of expert credibility weights in FCM and proposed a methodology [155, 156]. Their approach is based on calculating Hamming distance (bit difference) between inferences from various experts. The following two assumptions are made for developing this method:

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

The combined FCM (CFCM) is calculated using the Eq. 6 [155–157]:

$$CFCM = \sum_{i=1}^{NE} FCM_i \cdot W_i \tag{6}$$

where,

$NE$ Number of experts
$W_i$ Credibility weight of expert $i$
$FCM_i$ FCM matrix of expert $i$.

The step by step procedure to calculate the expert credibility weight is described below [155, 156]:

1. Generate 500 hundred random stimuli i.e. input vectors, initial condition vectors. For $n$ number of concepts, the input vector is 1 *by* $n$.
2. Excite each FCM matrix from these input 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.

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 (010100) and (011101) is 2. Hamming matrix ($H_{q,i,k}$) is symmetric with zero diagonal. One Hamming matrix is developed for each stimulus i.e. input vector.

3. Next step is to make a sum these 500 Hamming matrices according to the Eq. 7:

$$M_{i,k} = \sum_{q=1}^{NQ} \frac{H_{q,i,k}}{NQ} \tag{7}$$

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.

4. Then calculate the total Hamming distance of each expert. Hamming distance of expert i can be obtained from the Eq. 8:

$$h_i = \frac{\sum_{k=1} M_{i,k}}{(NE-1)} \quad \text{for } 1 \le \text{i, k} \le \text{NE} \tag{8}$$

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.

5. Last step is to calculate credibility for each FCM. So the weight of expert *i* is calculated using Eq. 9.

$$W_i = 1 - \frac{h_i}{\sum_{i=1} h_i} \qquad \text{for } 1 \le \text{i} \le \text{NE} \tag{9}$$

where $W_i$ is the *credibility* for expert *i* or credibility for *FCMi* proposed by expert *i*. Then combined FCM is calculated using the Eq. 6.

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 the approach proposed by Taber and Siegel, it will further suppress any weak signals if highlighted by a few experts. Thus, the expert credibility weight approach is suitable for healthcare sector where it is critical to achieve consensus; such as development of a diagnostic criteria for a disease. However, it is not a suitable approach for combining multiple FCMs developed for scenario planning.

Another method is commonly employed to combine multiple FCMs and it takes an average of the expert opinions expressed in all FCMs to generate integrated FCM [154, 158, 159]. This approach does not measure disagreement among the experts, but is recommended for combing multiple FCMs for the purpose of scenario planning [160].

## 10 Consistency, Reliability and Validity of the Delphi Method

It is important that reliable and accurate methods are used in a research. Reliability measures that a particular technique is applied repeatedly to same object and yields the same results each time [161]. Whereas, research validity means that we are actually measuring what we intend to measure or it is the extent to which a measure actually measures a trait [161].

The results of Delphi studies are generally considered to be reliable and various studies have demonstrated the validity and accuracy of the Delphi technique [49, 141, 162]. Reliability and accuracy of Delphi can be evaluated by comparing two or more Delphi studies on the same subject [54, 163]. Ono and Wedemeyer assessed the accuracy and validity of the forecasts derived from a classic Delphi study exercise [162]. They compared expert judgment of 24 trends and 17 events in the communication field with the forecasts made by utilizing the Delphi technique 16 years earlier and results indicated that earlier forecasts were significantly correlated with the present day trend assessment [162]. Some researchers consider this study by Ono and Wedemeyer as a valid proof of the validity of the Delphi method [141, 164].

Martino also provided evidence of consistency and accuracy of expert opinions through Delphi approach [163]. He investigated the consistency of Delphi studies on a same subject by different expert panels and made comparisons of published Delphi forecasts [163]. The results of these Delphi studies were compared and standard deviation of the differences were computed. It was found that for long range forecasts, the standard deviation was ranging from approx. 3.5 to 2.5 years which is considered a high degree of consistency [163]. Thus, based on this analysis and comparison, Martino concluded that the forecasts produced by the Delphi method are quite consistent and different panels tend to produce similar results [163]. He further states that it is unlikely that two panels of equally competent experts will produce significantly different forecasts.

The Delphi method is also criticized by some researchers due to lack of clear evidence of validity and reliability of the output of this approach [54, 72]. However, it is also not very clear in the literature as how to establish reliability and validity of the Delphi study [66, 165]. Landeta emphasizes that by effectively carrying out the Delphi process including careful selection of the experts, formulation of questions, and processing of data, significantly helps to achieve high levels of reliability and validity for a study [135]. Hill et al. and van Zolingen et al. also state that reliability is principally achieved through the standardization of research procedures [143, 166].

The literature review highlights that results of Delphi studies convergence after successive Delphi rounds and the general trend is toward more valid judgments over iterations [167, 168]. Thus, the feedback after every Delphi round increases the convergence of the individual judgments and overall validity of the individual expert is improved due to this information exchange [49]. Dalkey, Brown, and Cochran also found that the feedback improves the accuracy of the group estimates [169]. Moreover, due to anonymity, experts change their opinions due to objective and rational reasons without any pressure.

Reliability is usually defined in terms of the precision of measurement instruments and dependability of measurement across different replications [143]. There cannot be good scientific results without reliability [143]. Woudenberg state that factors such as the skills of the group leader, motivation of the participants, and quality of the instructions and questionnaires affect the validity of Delphi approach

[54]. Moreover factors like the number of experts and their expertise level are also very important [166].

A study was conducted to investigate the relationship between expert panel size and panel reliability and it was found that the mean correlation between the median and the true answer increases with increasing number of experts [48]. Correlation between actual measurements and expert opinions exceeds 0.70 when the panel size is 11 and no further change occurs after the panel size exceeds 15 [48]. Therefore, we can conclude that 11–15 is an optimum size of an expert panel.

During Delphi study long time intervals between one round and the next round could distort the research and dishearten the participants; thus, shortening this turnaround time periods improves reliability of the research [170]. Therefore, online Delphi approach is considered a better option because it shortens the overall time period of the study [58, 59].

Landeta et al., Hill et al. and van Zolingen et al. highlight that the reliability of expert judgment study depends upon the following factors [143, 166, 170]:

- Quality and expertise of the members of an expert panel
- Time elapsing between Delphi rounds
- Proper administration of the questionnaire and the feedback
- Ensure clear and standardized instructions without any ambiguity
- Clarity of questions
- Consensus/convergence of opinions
- Stability of the results between consecutive rounds.

As mentioned earlier that despite some criticism, it is evident from research that Delphi technique yields better predictions and accurate forecasts than another normal interacting group or a face-to-face committee meeting [68–70]. Landeta analyzes the published literature on Delphi approach over time and argue that its extensive use in scientific publications and doctoral theses indicates the validity of this method [135, 170]. It further highlights that the scientific community considers it as a valid technique for obtaining and processing subjective information from the experts, whether used alone or in combination with some other technique [165, 170]. Landeta also cites that large number of dissertations have used the Delphi method and according to data from ProQuest database, it has been used in 1668 dissertations during the time period from 1970 to 2004 [135]. It highlights the importance, usefulness and validity of Delphi technique for research.

## 11 Selection of Appropriate Research Method

It is critical to choose an appropriate technique for a particular application in a research project [171, 172]. Levary and Han highlight that selection of a technological forecasting method depends on factors such as: stage of technology development, degree of similarity between proposed and existing technologies, number of forecasting variables, extent of data availability, data validity, and technological uncertainty [172]. Chambers et al. highlight that selection of a research method also depends on factors like the context of the research, relevance and availability of historical data, degree of desirable accuracy, and the time available for making the analysis [171].

Based on an in depth analysis of nine case studies, Levary and Han conclude that Delphi method and scenario writing approaches are suitable in situations where there is no or low level of similarity between the proposed technology and existing technologies, a medium number of variables affect technological development, less data available, and low or medium degree of data validity requirements [172]. 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 Delphi method and/or scenario planning approach [172].

Rowe, Wright, and Bolger argue that Delphi allows the experts to make meaningful judgments, particularly in cases where a variety of factors (economic, technical, political and so on) affect the problem under consideration and it gives an opportunity to each expert to derive benefits from others experts having diverse knowledge and background [49]. It is very useful approach especially when no historical data exists for judgment [49]. The Delphi method is also very useful when it is difficult to bring experts together due to time or cost constraints [47]. Linstone and Turoff state that sometimes it is necessary to benefit from 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 [47].

Delphi is a powerful tool to engage stakeholders and it is an appropriate approach when there are many stakeholders because it is not possible to gather everyone in one place [61]. Woudenberg arranged the expert judgment methods in order of increasing accuracy based on a comprehensive literature review and found that the Delphi method is the most accurate technique among various expert judgment methods [54]. Various other researchers have also indicated that Delphi approach generate accurate and reliable judgment than other techniques [68–70, 163].

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# Technology Forecasting Methods

**Yonghee Cho and Tugrul Daim**

**Abstract** This study analyzes the origins and historical evolution and revolution of technology forecasting methods, a discipline that identifies the concept, assumptions and evaluates technology forecasting techniques with significant relationship between them. A variety of technology forecasting approaches, initiated in the 1950s, with the pioneering researches carried out by US department of Defense, and some researchers of The RAND Corporation. For over 1960 years, numerous technology forecasting methods have been developed and recently become a distinct field of investigation of future world. Mostly revolutionary techniques would have been to combine different methods characterized by the several disciplines, such as exploratory, normative and intuitive approaches. This paper proposes the gap of the main techniques of technology forecasting, developed over the course of time, identifying their methodological origin. Some concluding remarks and lessons learned complete the research.

## 1 Introduction

The future is uncertain and unstable at all times. Technological change also is associated with a high degree of uncertainty. Technology forecasting is continuously recognized as influences in the transformation of individual behavior, organization, economy, society and culture in such a turbulent world. Therefore, Government and companies should strive to predict the impacts which technology developments are likely to have on future society as well as business environment.

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To my knowledge, the first major attempts to forecast technological trends in the next 10–25 years on the new future inventions was developed by National Resource Commission (NRC) in 1935, which tasked a committee to predict the future of 13 major inventions in 9 different fields [168]. NRC study was commissioned during the Great Depression. S. Colum Gilfillan specifies 38 principles of invention which afford a potential framework for the prediction of technological progress at “The Prediction of Inventions” and “Social Effects of Inventions” book chapter of this report [82, 133]. On December 7 1941, US Air Force and Army countered threat by Japanese’s sudden and devastating raids to Pearl Harbor. This unpredictable and unforgettable attack asked US Air Force to assemble a group of top scientists to review aeronautical research and make recommendations about the future of air force in light of probable scientific opportunities in the decades to come [89]. Since 1945 much of work in Technology Forecasting has been developing as a discipline and planning tool, initiated by US Department of Defense, a few aerospace firms, and specialized consulting firms [22, 153]. In the 1950s and 1960s, Technology Forecasting was driven by military competition with the Soviet Union, specifically following the “Sputnik Crisis” in 1957. The objective of technology forecasting is to anticipate the technological capability of enemies for the defense planning at this time. In other words, Technology forecasting was initiated primarily as a tool to help anticipate military technology needs and to help plan and prioritize R&D and systems development [178].

Since early or mid 1960, numerous technology forecasting methods have been developed to alleviate the risk and to obtain reliable and sufficient evidence. With the strong confrontation of technological change, U.S. Air Force put much effort to develop TF techniques and provide unprecedented long range planning, mainly published by Ralph C. Lenz, Jr., who was head of the Dayton Research Institute’s Technological Forecasting Program, and Joseph P. Martino, who was chief of the Environmental Analysis Division of the Air Force Office of Research and Analysis, as well as its think tank, The RAND Corporation which developed Delphi method [137]. Companies such as Douglas and Lockheed, its aerospace contractors, also made some efforts on technology forecasting [137]. Historically, a number of technology forecasting is of much interest to government and to other research institutions, and most of them are used to plan technology policy for specific R&D program and to progress the government agendas. Therefore, many governmental organizations have adopted and developed various technology forecasting and foresight methods and practices.

Hal Linstone pointed out that technology forecasting seems to have peaked around 1970 with a decline in methodological advance thereafter [41]. The limits of systems analysis became evident and the influence of the RAND brain trust waned [137]. In 1972, the Office of Technology Assessment (OTA) was established as an arm of the U.S. Congress to provide resourceful analysis of the intricate and scientific and technical matters. Post cold war, a military or political competition ended, public policy initiatives and national security are main drivers of technology forecasting to predict future technological change as a means to secure a decisive competitive market in the world.

On the other hand, the primary needs of technology forecasting shifted from government to the companies. In 1968, Erich Jantsch wrote that the company started to focus on the integration of technological forecasting with long-range planning, and the implications for organization structure and operations [22]. Furthermore, with the rapid change of technology platform, while many companies are integrated with other functions and government policies, technology forecasting activities such as the technology roadmap, business/technology strategy, and information technology (competitive technological intelligence) has gained more significance than the accuracy of prediction. In practice, technology forecasting is inevitably needed to help to identify and assess opportunities and threats in firms' competitive business environment in R&D portfolio and New Product Development and creating strategic alliances such as licensing and joint ventures. TF is imperative to corporate planning group and R&D laboratories not only to formulate business and technology strategy but to review R&D program.

A variety of technology forecasting methods have been developed and applied to various industries, organization by diverse purposes. The corporate has made its efforts on environmental scanning such as bibliometric/patent trend analysis and market analysis to indentify increasingly diversified needs of customers, in order to establish a steady grasp of technology initiatives as well as to improve its future position. In addition, a company should set up R&D strategy in alignment with business strategy such as manufacturing, sales and marketing, personnel, finance, and accounting. The key of business success is to provide differentiated product to customers for a firm to survive in tornado world market, compared to competitors. Systematic technology innovation management should be established, based upon the prediction of technological change and speed. The first step starts from forecasting activity. In the last four decades, especially after the widespread availability of Information Technology, some of the different approaches using much information like patents, journals, and research awards, have been continuously developed by different researchers combing with many other tools. Alan Porter presents an illuminating bibliometric analysis of the methodology trends that confirm some of our perceptions.

The research questions with which I started this exploration of technology forecasting methods are:

- What kinds of techniques and approaches are employed chronologically?
- What is the historical trend in terms of technology forecasting methods?
- Which methods are combined with each other?
- What kinds of characteristics of these methods?
- What applications are in technology forecasting domain?
- What kinds of data and techniques have been developed to improve the accuracy?

The first thing to do is to choose the right forecasting method which is most appropriate to the analysis and technology characteristics such as disruptive versus incremental technology. It would depend on uncertainty surrounding technology development, data availability, technology difficulties, funding for R&D.

Technology Forecasting is categorized as an explorative and a normative technique. The study reviews the various methods with respect to TF. Finally, this study attempts to answer research questions and provide some aspects on how to integrate two or more approaches into decision making process.

The paper is organized as follows. In Sect. 2, the general background of Technology Forecasting methods are presented. Section 3 describes the characteristics such as their inception, original reference, assumptions, limitations, advantages, and disadvantage with respect to each method. Finally conclusion and recommendations for future research are discussed at Sect. 4. I hope this study will be of value to a variety of R&D managers and government policy-makers.

## 2 Literature Review

### A. The concepts of technology forecasting and technology foresight

There is little agreement in terms of the meaning of the "technology forecasting" and "technology foresight" with relatively little effort to clarify their similarities and differences [41]. Historically, the term technological forecasting incepted around Mid 1940 is more often and longer used in literature than technology foresight coined in the early 1980s [94]. These two terms has been interchangeably used in some scattered literature in the last decade. It may obscure future research, thus a comprehensive review of them is necessarily valuable at this juncture. The study first clarifies the historical concept and potential misinterpretations of these two concepts.

Technology forecasting is different from social forecast, economic forecast, market forecast, financial forecast, transportation demand forecast and weather forecast, but in some contexts, it also intertwine with them [185, 215]. What is the technology? Webster dictionary defines it as "The practical application of science to commerce or industry". "Technology" can be regarded as a quite specific physical entity. In some sense, it does not include tacit knowledge embodied in human beings by definition. However, Quinn explains more precisely technology as "not a single immutable piece of hardware or bit of chemistry, but also knowledge of physical relationships—systematically applied to the useful arts" [185]. "Forecast" is to predict how something will develop. Forecasting normally ends with the identification of the possible futures. The definitions of technology forecasting vary to a certain extent. In 1962, Lenz, one of the pioneers of technological forecasting, defines technological forecasting as "the prediction of the invention, characteristics, dimensions, or performance of a machine serving some useful purpose…. The qualities sought for the methods of prediction are explicitness, quantitative expression, reproducibility of results, and derivation on a logical basis" [133]. In 1967, Jantsch who was a consultant to the OECD, defines technological forecasting as "the probabilistic assessment, on a relatively high confidence level, of future technology transfer" [111]. It more focus on the technology transfer standpoint. Bright wrote technology forecasting means "systems of logical analysis that lead to common quantitative conclusions (or a limited range of possibilities) about technological attributes and parameters, as well as technical–economic attributes" [22]. Cetron explain technological forecasting in more detail as "the prediction with a level of confidence of a technical achievement in a given time frame with a specified level of support" [34]. Martino defines technology forecasting as "a prediction of the future characteristics of useful machines, procedures or techniques i.e., technology is not restricted to hardware only, but may include "know-how" and "software" [153]. It is focused on practical application and not purely scientific knowledge. Ascher defines technology forecasting as the effort "to project technological capabilities and to predict the invention and spread of technological innovation…." [7]. In addition, Millett and Honton expand the concept of technology forecasting as "the process and result of thinking about the future, whether expressed in numbers or in words, of capabilities and applications of machines, physical processes and applied science" [160]. It includes business environment and corporate concerns as well as technological performance.

To sum up the concept of technology forecasting mentioned above, technology forecasting is to analyze and evaluate performance parameters, timing of advancements, new concepts, products, processes, market penetration and sales in a given time frame with probability statements, on a relatively high confidence level, by capturing technology opportunities/threat from technological changes in order to provide a valuable information for a better decision-making of R&D.

The main objective of technology forecasting is to support decision making as well as R&D and business planning. Swager identified five roles of technology forecasting: Identifying policy option, Aiding strategy formulation, Identifying program options, Selecting programs for funding, and Selecting opportunities for investment [228].

On the other hand, Historically, foresight and forecasting were used interchangeably more or less as a synonym [94, 168], but meanwhile, there is a real difference in the understanding of forecasting compared to foresight [42]. the term technology foresight or national technology foresight has increasingly been used to signal the role national governments are playing in identifying socially desirable technologies [41]. Technology Foresight goes further than forecasting, including aspects of networking and the preparation of decisions regarding the future [42]. That is why foresight focused attention on a national scale in many countries. Foresight not only looks into the future by using all instruments of futures research, but includes utilizing implementations for the present [42]. In 1985, Joseph Coates identifies foresight as "the overall process of creating an understanding and appreciation of information of varying degrees of credibility, completeness, and technical and scientific soundness generated by looking ahead" [39]. In 1995, Ben Martin defines technology foresight as "the process involved in systematically attempting to look into the longer-term future of science, technology, the economy and society with the aim of identifying the areas of strategic research[1] and the emerging of generic technologies[2] likely to yield the greatest economic and social benefits" [145]. The ultimate objective of foresight is to ensure that areas of science and technology that are likely to yield future socio-economic benefits such as health, quality of life, environmental protection and contributions to culture are identified promptly [145]. Since 1990s, technology foresight activity has been actively and broadly implemented in Europe. In some European context, networking and cooperation in identifying future options is as—in some cases even more—significant than the tasks of forecasting [42]. The summary of concepts of them follows as Table 1.

B. **The subsets of technology forecasting**

***Characteristics of technology forecasting***

Technology forecasting consists of subset elements such as a certain future time span, technological change, continuous range of characteristics in applications, and a statement of the probability associated with the technology [153]. Technology forecasting do not necessarily need to predict the exact form of technology dominating in a given application at some specific future date, since technology forecasting aims to provide the evaluation of the probability and significance of various possible future developments in order for managers to make better decisions [185]. In most cases, technology forecasting is wrong. Technology forecasting, however, is valuable to give guidance for the direction of promising technology development. The value of technology forecasting lies in its usefulness for making better decisions, not in its coming true [153]. Technology forecasting, in other words, typically partially correct and cannot include all exact future forms. Technology forecasting strives not only to identify research and knowledge gaps to find the right path to reach goals, but to search ranges of environment that will be encountered in the future.

***Assumptions of technology forecasting***

One of the most significant thing is to decide the right assumptions and appropriate methods to a given situation, so as to predict the right technological change in a certain future, since technology forecasting results are inevitably affected by the methods employed [161, 135]. It mainly affects the accuracy and reliability of technology forecasting. If the assumptions are inaccurate, the prediction would go wrong way. However, some analytical gain in forecast accuracy achieved by the use of a complex method is likely to be futile by the messy arena of world. It requires a technique that is suitable for such characteristics of a certain technology, since technology forecasting deals with ill-structured problems [162]. In addition, many forecasters put efforts in increase of sophistication as well as

[1] 'Strategic research' is defined as "basic research carried out with the expectation that it will produce a broad base of knowledge likely to form the background to the solution of recognized current or future practical problems" [108], p. 4.

[2] 'generic technology' is defined as "a technology the exploitation of which will yield benefits for a wide range of sectors of the economy and/or society" [148], p. 51.

**Table 1** Technology forecasting vs Technology foresight

| Term | Definition | Characteristics | Elements | Type of affiliation(inception) | Nation | Citation |
|---|---|---|---|---|---|---|
| Technology forecasting | A prediction of the future characteristics of useful machines, procedures or techniques i.e., technology is not restricted to hardware only, but may include "know-how" and "software | Prediction, Not necessarily assessments, More quantitative than qualitative, No information about consensus necessary, Less dependent on opinions<br>Identification of possible futures | (1) The time of the forecast<br>(2) The technology being forecast<br>(3) A statement of the characteristics of the technology<br>(4) Statement of the probability associated with the forecast | 1. Government<br>2. Academia<br>3. Industry | US (1937), EU[Netherland (1949), France (1961), Germany (1964), Italy (1965), Switzerland (1965), Austria(1966)], Israel (1954), Canada (1960s), UK (1963), Japan (1975), China (1985), South Korea (1990s), India (1997) | [22, 42, 111, 153, 40–161, 185, 219] |
| Technology foresight | Process involved in systematically attempting to look into the longer-term future of science, technology, the economy and society with the aim of identifying the areas of strategic research and the emerging generic technologies likely to yield the greatest economic and social benefit | Outlook, The communication or procedural power, A bundle of systematic and comprehensive process to look ahead, Many possible futures<br>Criteria for assessments, More qualitative than quantitative, Finds out if there is consensus on themes, Very dependent on opinions, Neither too general nor too detailed, Process must be public | (1) Direction-setting<br>(2) Determining priorities<br>(3) Anticipatory intelligence<br>(4) Consensus generation within research community or externally among research funders, performers and users<br>(5) Advocacy for a new research initiative<br>(6) Communication and education within the research community | 1. Government<br>2. Academia<br>3. Industry | Japan (1971), US (1980s), Canada (1980s), EU[Netherlands (1988), Germany (1991), France (1994), Spain (1995), Italy (1995), Hungary (1997), Austria (1997), Norway (1998), Sweden (1998), Portugal (1999), Denmark (2000), Finland (2001)], New Zealand (1992), UK (1993), Australia (1994), South Korea (1994), China (2002) | [41, 14–132, 42–145, 146, 147, 149, 157, 164, 240 ] |

quality of data to resolve problems generated by technology forecasting. However, only data from the past and present is available. Most of them are not caused by a lack of sophistication but by drawbacks in the process of technology forecasting itself [198]. One of the mistakes of technology forecasting is to assume that the future is fixed or pre-determined. Furthermore, the main mistake of trend projection will be driven by assumption that the future will simply be an addition or subtraction from the present, based upon philosophical background that technology will follow past trends. It ignores the effects of unprecedented future events.

***Technological trajectory vs Discontinuity***

It is necessarily of vital importance to understand how technological change develops and happens for the appropriate use of technology forecasting. Kuhn address that the normal development path of scientific knowledge is heavily selective with respect to a major framework jointly adhered to by the leading scientist in the field [131]. Technological change is more often argued to depend on the evolution of trajectory [66], so called technology trajectory. It is inherently based upon the cumulative nature of learning processes. Giovanni Dosi defines a technological trajectory as the pattern of actualization of a promise contained in a scientific paradigm solving activity (i.e. of "progress") on the ground of a certain technological progress, in other words, technological trajectory is a cluster of possible technological directions whose outer boundaries are defined by the nature of the paradigm itself [52]. He also describes "technological frontier" the highest level reached upon a technological path with respect to the relevant technological and economic dimensions [52]. Christensen explains the concept of performance trajectories as the rate at which the performance of a product has improved [17]. Technology trajectory reflects aggregation of technological advances, following on established technological paths.

On the other hand, disruptive or discontinuous technological innovation is different from technological development following on technology trajectory. Technological discontinuity originally results from the substitution of technological rivalry among competitive technologies [2]. Life cycle of sustaining technological advance may be disrupted by subsequent technological breakthrough. In this case, traditional approach of technology forecasting with probability statement is not appropriate for the prediction of discontinuous emerging technology. Discontinuous technological change can be defined as scientific discoveries that breakthrough the usual product/technology capabilities and create an entirely new market through them [17–36]. It is very crucial to forecast disruptive technologies for decision making on firm's R&D investments and business plan for commercialization efforts. It is, however, very ambiguous to predict the right time and disruptive technology to change existing technology trajectory. Therefore, technological change to forecast can be divided into "continuous" and "discontinuous" which are associated with the emergence of a new paradigm, and can be interpreted "incremental innovation" versus "disruptive innovation".

## C. The classification of technology forecasting methods

In 1967, Erich Jantsch classified the technology forecasting methods as intuitive, exploratory, normative, feedback techniques with viewpoint of technology transfer [111]. In 1991, Stephen Millett and Edward Honton organized technology forecasting techniques into trend analyses, expert judgment, and multi-option analyses [160]. John Vanston assorted technology forecasting techniques as 5 different approaches such as extrapolators, pattern analysts, goal analysts, counter-punchers, and intuitors [242]. The TF methods are commonly classified under the headings of 'exploratory' or 'normative' [196, 237]. This study divides TF techniques into normative, exploratory, and the combination of two groups, according to Technology Futures Analysis Methods Working Group [232] (See Table 2).

Exploratory technological forecasting is the attempts to predict the technological state-of-art that will or might be in the future [196]. It starts from today's assured knowledge of what has happened in the past up to the present day and is predicting towards the future events. It includes those methods based upon an extension of the past through the present and into the future. It is more focused on predicting how a new technology will evolve on a predetermined curve, which is S-shaped growth curve. In some sense, exploratory forecasting is regarded as illustrating the inevitable future, so that there is little left to affect or alter through planning [22].

**Table 2** The classification of technology forecasting methods

| Term | Definition | Characteristics | Citation |
|---|---|---|---|
| Exploratory | The attempts to predict the technological state-of-art that will or might be in the future | - evolve on a predetermined curve such as S-shaped<br>- too naïve<br>- project anticipated consequences<br>- suggest alternatives to the proposed allocation | [196, 232] |
| Normative | The statement of what ought to be or needs to be possible at some future time | - more proactive<br>- too complex and mathematically intricate<br>- meaningfulness of its treatments of goals is significant<br>- recognition of economic potentials<br>- recognition of responsibility towards society or nation<br>- awareness of constraints (natural resources, company resources, etc.)<br>- recognition of an ultimate technological potential<br>- hedging against threats | [196, 232] |
| Normative/Exploratory | Can be used in two different approaches | – | |

On the other hand, normative technological forecasting first assesses future goals, needs, desires, missions, etc. and trace backward to the present at some desired or possible state of events not only determining steps necessary to reach the end point, but also assessing the probability of their success [196]. It starts from the future backward. The mind is projected forward from today taking into account the dynamic progression or events represented by the accomplishment of a particular mission, the satisfaction of a need, or state of technological development. It mainly focuses on the possible statements that what ought to be or needs to be realized at certain future time. Normative technology forecasting aims to provide groundwork to allocate technology-generating resources such as investment, human resource and others in order to reach organizational objectives. Typical characteristics that lead to exploratory as well as normative forecasting include the following.

D. **Exploratory forecasting methods**

In the early ages of TF, the attempts to forecast technological change mostly involved exploratory approaches and Delphi [133, 152]. Exploratory technology forecasting methods simulate movement in the direction of technology transfer [111]. Following description of each technology forecasting methods attempt to provide a basic knowledge for its practical applications.

- **Trend extrapolation**

Trend extrapolation is one of widely used techniques for technology forecasting. Extrapolation technique reflects that the future will be a reasonable projection of some type of time-series data, based on the assumption that the old time-series includes all the information needed to predict the future event, and existing trends will continue in the future, not producing different pattern [133, 153]. A number of economic forecasts are based on this assumption.

First of all, forecasters need to collect an appropriate data in terms of an attribute or variable over time, and then they can easily predict the future by identifying previous trends and extrapolating them in an intelligent manner. It attempts to find some kinds of patterns such as trends or cycles in historical data by fitting a relevant curve to the past data. Therefore, the selection of the appropriate fitting curve for extrapolation is crucial to forecasting success [154].

There are three types of curve-fitting equations for trend extrapolation based on the rate of technological progress of historical data—linear, exponential and polynomial techniques [8]. Linear Extrapolation is used where a linear growth function is predicted. A polynomial trend equation may be applied to identify the trend where the trend does not follow either a linear or exponential. Once forecasters choose an appropriate equation, an extrapolation can be portrayed mathematically and graphically (Table 3).

Forecasters has used trend extrapolation to predict technological capabilities, the rate of technological change, level of product sales, and the length of time it will take to develop a new technology, among many other events, on the basis of available variables and data [160]. This method is closely associated with growth

**Table 3** Types of extrapolation technique

| Types | Curve-fitting equation | Characteristics | Reference |
|---|---|---|---|
| Linear | $Y_{t+1} = y_0 + kt$ | - simple and relatively inexpensive | [8, 133, 153, 160, 210] |
| Polynomial | $Y_{t+1} = y_0 + k_1t + k_2t^2$ | - easy to understand | |
| Exponential | $Y_{t+1} = y_0e^{kt}$ or $\ln y_{t+1} = \ln y_0 + kt$ | - inaccuracy<br>- appropriate for short-term forecast<br>- not applicable for discontinuous technology<br>- needs conjunction with complementary methods | |

curve fitting and projection. Trend extrapolation is recommended to be employed in conjunction with normative forecasting methods such as cross-impact analysis, expert opinion and monitoring, in order to improve forecasting accuracy [182].

- **Growth Curves; S-Curves**

The growth curves are the oldest techniques, and also widely used in practical applications for technology forecasting. The growth curves typically exhibits an "S-shaped" characteristic like life cycle over a period of years, since technologies tend to evolve on patterns similar to the growth curves of biological systems from experience [153, 197]. They also extrapolate it, based on the current and past trends, in a deterministic way. It associates with fitting a growth curve to a set of data over time of technological characteristics. A number of growth curves have been developed to predict technological advance. Logistic and Gompertz curves among them are most commonly used methods, having long history of their inception in demography field and later applied to technology forecasting. Growth curves have continuously gained popularity due to relative simplicity, long history of use in various fields, and the modality of the assumption that historical data can be good guidance to technology trajectory [13].

Growth curves are based on three assumptions [153]:

- The upper limit to the growth curve is known; the upper limit of technological change can be set by natural, fundamental, physical and chemical laws that rule the phenomena used in the technical approach
- The selected growth curve to be fitted to the past data is correct enough to predict technology trajectory
- The historical data gives correct coefficients of the chosen growth curves equation; much effort is needed to find representative coefficients based on the historical trend [160].

Growth curves presume a technology will finally reach its upper limit at a certain time, and are employed to forecast how and when a technical will reach its upper limit. It reflects that growth is slow initially until difficulties are overcome then growth is more rapid until the limit is approached with growth slows down again. Therefore, it is critical to estimate the upper limit using historical analogies. At this juncture, the previous experience with a similar technology is a key to forecast technologies more accurately [160]. Furthermore, Growth curves estimate a single variable. If a technology reaches a upper limit, a new technical variable create a new growth curve completely [153]. These approaches are also appropriate for a short-term forecasting.

Like life cycle, substitution curves are a type of growth curve that project the substitution of one technology for another or the rate of penetration of some technology into a market [64, 152]. Since Mansfield, as a pioneer, proposed technology diffusion model incorporating the rate of imitation and technology adoption, a variety of growth curves such as the Mansfield-Blackman model, the Fisher-Pry model, the Extended Riccati model, the Bass Model, and etc., have been developed to forecast S-shaped pattern of technological advance [144]. For the purpose of analysis, main issue is to determine curve slope as well as inflection point using a time series of data. Selecting an appropriate equation of growth curve is somewhat arbitrary. That is why most forecasters experiment various growth curves to find the most relevant curve fitting to predict the technological change [155] (Table 4).

- **Bibliometrics; Scientometrics**

***Literature analysis***

McKeen J. Cattell, a pioneer as a psychologist, first used literature data to measure performance and productivity of scientists in 1906 [33]. There were some bibliometric studies around 1920, using statistical techniques, although using the older terminology 'bibliography' [102]. The term 'Bibliometrics', however, was coined from Pritchard who introduced it to replace 'statistical bibliography' in 1969 [183]. In this article, Pritchard defines bibliometrics as "the application of mathematical and statistical methods to books and other media of

**Table 4** Types of growth curves

| Types | Equations | Inception | Reference |
|---|---|---|---|
| Logistic or Pearl | $Y = \frac{L}{1+ae^{-bt}}$ | 1923, 1957 | [90, 197] |
| Gompertz[a] | $Y = Le^{-b-kt}$ | 1932 | [249] |
| Mansfield- Blackman | $\ln\left(\frac{Y_t}{L-Y_t}\right) = \beta_0 + \beta_0 t$ | 1961, 1972 | [13, 144] |
| BASS | $y_t = \frac{\left[1-e^{-(p+q)t}\right]}{\left[1+(\frac{q}{p})e^{-(p+q)t}\right]}$ | 1969 | [11] |
| Fisher-Pry | $\frac{Y_t}{1-Y_t} = e^{2a(t-t_0)}$ | 1971 | [64] |
| Extended Riccati | $\frac{y_t}{Y_{t-1}} = \beta_0 + \beta_1 Y_{t-1} + \beta_2\left(\frac{1}{Y_{t-1}}\right) + \beta_3 \ln(Y_{t-1})$ | 1976 | [136] |
| Weibull | $\ln\left(\ln\left[\frac{L}{L-Y_t}\right]\right) = \beta_0 + \beta_1 \ln t$ | 1980 | [218] |
| NSRL[b] | $\ln y_t = \beta_0 + \beta_1 \ln(Y_{t-1}) + \beta_2 \ln(L - Y_{t-1})$ | 1981 | [53] |
| Harvey | $\ln y_t = \beta_0 + \beta_1 t + \beta_2 \ln(Y_{t-1})$ | 1984 | [96] |

[a] Gompertz named after Benjamin Gompertz, an English demographer, who originally proposed the model as a law governing mortality rates in 1825.
[b] NSRL: Non-Symmetric Responding Logistic.

communication". There are various definitions illustrated by numerous researchers. One of the general definitions is "the search for systematic patterns in comprehensive bodies of literature" [83]. Bibliometric techniques are initially employed in the field of library and information science. Bibliometrics initially focus on statistics with respect to the production, distribution and usage of literatures, rather than the contents of a set of research publications [140]. Bibliometrics aims to analyze the impact of different fields and a set of researchers through exploring a wealth of historical literature data. In the context of technology forecasting, however, bibliometrics can be defined as the research of statistical analysis to produce and disseminate the information with respect to the use of recorded literatures for forecasting and decision making. This technique helps to identify the most recent technological trends and discover hidden patterns with the information of authors, affiliations, and recent researches in literatures.

On the other hand, in 1969, Vassily V. Nalimov and Z. M. Mulchenko started to use the term 'Scientometrics' which is mainly employed for the research of all aspects of the literature of science and technology [102]. This term has been widely recognized by the Journal 'Scientometrics' established by Tibor Braun in 1978. Scientometrics involves sociology of science and science policy, using qualitative, quantitative and computational methods [231]. It appears bibliometrics conceptually includes scientometrics to quantitatively analyze scientific and technological literature. These have very much similarity in employing mathematical models. Scientometrics, scientific literature analysis, also analyze data on the publications of researchers not only to measure R&D activity, impacts, and intellectual linkages as a valid indicator of science and technology [167], but also to identify emerging research fields for forecasting [12, 165].

Bibliometrics is typically classified in descriptive research (regarding the characteristics of a type of literature) and behavioral studies (investigating the relationships involving between elements of a type of literature) [83]. Since Science Citation Index was established in 1961, systematic analysis has been possible and prevalent, using a wealth of data. In addition, Compendex, Computerized Engineering in DEX, also was started in 1970 as an Engineering Index which provides a comprehensive engineering bibliographic database. The rapid evolution of information technology enable for researchers to predict the technological advance. Bibliometrics has been popularized and becoming more significant in technology forecasting over the years with the advancement of DB system [124, 125]. Alan Porter presents an illuminating bibliometric analysis of the methodology trends that confirm some of our perceptions [181].

The basic process of bibliometrics [160]:

- Define the technology area
- Establish the problem domain (year, year of publication)
- Search all scientific and technical publications for relevant articles
- Load relevant data (article title, abstract, author names, references given, country, etc.)
- Analyze the database

- Analyze the implications of indicators.

Typical approach of bibliometrics has been retrospective to trace relationship such as counts, co-occurrence and citations among publications for the evaluation. Since 1927, various types of bibliometric tools have been developed to analyze descriptive statistics, affiliation, authors, countries, and collaboration of literatures. The major derivatives of bibliometrics are publication counts, citation counts, citation network, co-citation counts, co-word counts, and scientific mapping (cartography). Since D. Price first analyzed the literature linkage using citation index to identify scientific structure, bibliometric citation network analysis has been used to identify research gaps and track emerging research fields in literatures [116, 117]. The concepts of these techniques are as follows:

- Publication count: the counting of scientific publications published by a researcher or a research group
- Bibliographic coupling: one item of reference used by two papers
- Citation analysis: the examination of the frequency, patterns, and graphs of citations in articles and books
- Co-citation analysis: the frequency with which two items of earlier literature are cited together by the later literature
- Co-word analysis: counts and analyze the co-occurrence of keywords in the publications on a given subject
- Data tomography: an information extraction and analysis system which operates on textual databases, which is keyword-based or index word-based full-text co-word analysis.

Bibliometrics can help to measure the impact, productivity, R&D activity and scientific and technological advances of specific areas or authors. Technical reports and scientific papers are appropriate literatures to capture the early stage of technology development [21, 154]. High citation is broadly used as an indicator of scientific emergence and significance of prior cited literatures (Table 5).

***Patent analysis***

There are much more similarities than discrepancy between literature biliometrics and patent bibliometrics [166]. Patents provide complementary information in bibliometrics. Patent data have valuable information such as geographical distribution of particular inventions, citation networks and patterns in terms of particular technology in order to monitor technological trend as well as innovative activities and new product development for forecasting [31, 59]. Patents are public record and every patent granted since 1836 has been assigned by the Classification Division to its corresponding class and subclass. US patent system, the largest patent system in the world, has been fully computerized since 1975 [167]. It is significant to understand the classification system used by the U.S. Patent Office in order not to include the wrong classification code or excluding one. The US Patent Office founded US Office of Technology Assessment and Forecast (OTAF) in the mid 1970s. It provides statistical patent information applied for since 1963 [171]. In 1970, United Nations founded World Intellectual Property Organization

**Table 5** Types of bibliometric analysis using literature

| Types | Characteristics | Inception | Reference |
|---|---|---|---|
| Citation | - impact factors, number of references, number of citations, | 1927 1961(SCI) | [93] |
| Lotka's law | - $f(n) = k\frac{1}{n^2}$; scientific productivity law (n; number of papers)<br>- a number of papers attributed to specific scientists | 1926 | [141] |
| Zipf's law[a] | - f(n) = k/n; word frequency law<br>- the descriptive evaluation of subject authority files and related aspects of indexing | 1932 | [254] |
| Bradford's law | - f(n) = k ln(1 + bn); bibliographic scattering law<br>- the cumulated total of papers in the first n of the ranked journals are arranged in descending order of productivity, | 1934 | [19, 24] |
| Bibliographic coupling | - meaningful relation to each other, when they have one or more reference in common<br>- based on citation indexing | 1962 | [120, 121] |
| Citation network analysis | - identify scientific structure<br>- identify research gaps and track emerging research fields | 1965 | [48] |
| Co-citation | - author connections, subject structure, networks, maps<br>- cluster co-citation<br>- time-consuming and expensive<br>- comparing lists of citing documents in the SCI<br>- more limited internal description of the state of each field | 1973 | [223, 97–222] |
| Co-word | - evolution and patterns of interactions of different subject areas<br>- description of subject area<br>- analysis of research trajectory<br>- time-consuming and expensive<br>- rather more inclusive, contextual, pictures of scientific activity<br>- mapping the structure of scientific research<br>- interaction dynamics of a research field | 1979 | [28, 29, 97–191] |
| Co-classification | - the network of interdisciplinary links between research fields<br>- the co-occurrence of different subject-classification<br>- the strength of interdisciplinary relations<br>- map of the interdisciplinary structure in a single field and whole area<br>- the level of interdisciplinarity in contributing research field | 1987 | [188, 173–234] |

[a] If words are ranked according to their frequency of occurrence (f), the n-th ranking word will appear approximately k/n times where k is a constant.

(WIPO) which is one of the specialized agencies of it, after conventional signature at Stockholm in 1967. WIPO also established the International Patent Documentation Center (INPADOC) with the agreement of Austria government in 1972, which was integrated into the European Patent Office in 1991. The INPADOC database provides information with respect to patent families as well as patent application in different countries. Furthermore, the advancement of IT (Information Technology) enables numerous researchers to measure the rate of technological change by actual uses of patent data. Patent data cannot simply generate a time-series of technology trends in particular areas, but also detect novel technological developments that could represents opportunities or threats to companies.

To the best of my knowledge, the first attempt to analyze patents statistically was made by Applebaum in 1920s [6]. Thereafter, a number of studies have used patents to measure innovativeness and difference, technological advance, and the rate and direction of technology development since 1930s [32, 112–209, 207, 224]. Gilfillan used the inventive cycle of patent as a technique for technology forecasting in 1935 [81, 82]. With respect to patent statistics, cumulative or actual patent counts in application or grants, a time-series of patent trend, and percentage of patents in total are most widely used in a measure of innovativeness, a rate of technological change, and research output [171, 91–189, 208]. Patent trend analysis provide growth pattern of a technology with the lifecycle of it.

Patent citations has been typically used as indicators of the importance of innovations, technological influence and diffusion of technology [119, 236]. The citation analysis, however, is somewhat different from literature citation one, in that it has two different references; applicant citations and examiner citations are used to refer and decide novelty, similarity and relevance [78]. Patent citation network analysis has also been used to identify the trajectory of a technological subject and explore dynamics of technological change [55, 65]. Patent co-word analysis was first used to improve evaluation of the contents of a large number of patents in biotechnology [27]. Co-word analysis technique provides research network map in patents which illustrate co-operation, recent technology trend in various sub-field and promising research directions. In the early 1980s, Battelle devised various patent analysis tools for technology forecasting such as Immediacy,[3] patent activity,[4] and patent clustering[5] [31]. The Battelle's process of patent trend analysis [160]:

- Define study objective
- Establish the problem domain (research framework, patent categorization scheme, etc.)

[3] It measures the age of the closest prior art in technical and scientific papers or in patents.

[4] It represent the number of patents in a given period to find an increasing or decreasing number of firms and inventors coming into a specific area.

[5] It looks how the patents in an area are connected together by citations with a network analysis.

- Obtain relevant patents (keyword, patent office classification, citation data, abstract review, full text review)
- Load patent data into software
- Produce computer output
- Interpret analysis results (innovation activity, dominance, company characteristics, portfolio analysis, etc.).

- **Data mining; Text (data) mining**

Through rapid evolution of information technology as well as flood of data, Data Mining (DM), Text Mining (TM), Tech Mining, Database Tomography (DT) have become practical techniques for assisting the forecaster to identify early signs of technological change [22, 43, 89, 140–165]. In literatures, Lovell, Michael C. first used the term 'Data Mining' to propose econometric data mining in statistical variables' tests in 1983 [142]. Gregory Piatetsky-Shapiro introduced the concept of Knowledge Discovery and defined it as "the nontrivial extraction of implicit, previously unknown, and potentially useful information from data" [60]. Data mining can be identified as a subset of Knowledge Discovery in Database (KDD), since KDD process is comprised of data preparation, data selection, data cleaning, data mining, incorporation of appropriate prior knowledge and proper interpretation of the results [61]. Data mining is identified as a particular element which extracts patterns or models from massive amounts of data with the application of specific computerized algorithms in KDD process [60, 140]. Data mining is defined as extracting useful information and detecting interesting correlation and patterns from any form of data, especially numeric data. Data mining has been theoretically built on the groundwork in database, machine learning, pattern recognition, statistics, artificial intelligence, information retrieval, reasoning with uncertainty, and knowledge acquisition for expert systems [60, 163] (Table 6).

Data mining typically makes use of structured database. Textual data mining, however, is concerned with the process of extracting interesting and non-trivial patterns or knowledge from unstructured text documents [63]. Text mining appears a subject of data mining, since text is just different form of data. Textual data mining is a much more allegedly difficult activity than numeric data mining, since it elaborate on handling textual database which are inherently fuzzy and unsymmetrical. Classification and indexing is never completely accurate. Text Mining serves as a powerful technique to explore textual database, discover useful and understandable patterns within them and automatically extract meaningful information from unstructured textual data. Text mining has been used to discover particular pattern of large-scale database and analyze technological trend. Analyzing the technology performance in specific field using keywords or phrases can provide an insight for technology forecasting. In recent years, text mining tool has gained popularity to explore the textual based documents such as literature and patents in biliometrics [130].

Kostoff and his colleagues in the Office of Naval Research developed data tomography which has a system and algorithms to analyze a large amount of

**Table 6** Types of patent analysis

| Types | Characteristics | Inception | Reference |
|---|---|---|---|
| Citation | - impact factors, number of citations<br>- two kinds of reference citations; applicant citations are occasionally provided by inventor, examiner citations are made more frequently by the patent examiner to warn the applicant of related work<br>- forward/backward citations | 1949 | [78, 217] |
| Patent citation network | - represent patents and their respective citations as a network<br>- use critical node, core network, and network topological analysis | 1978 | [55] |
| Co-citation | - map the inter-related development of technical fields<br>- assess the similarities in their patents | 1988 | [172, 227] |
| Co-word | - interaction between basic and technological research<br>- analysis of research trajectory<br>- describe life cycles<br>- evolution and patterns of interactions of different subject areas | 1986 | [27, 30] |
| Co-classification | - co-classification mapping<br>- belong to a fixed classification scheme, so might be out of date<br>- simplicity<br>- possibility to evaluate the existing classification schemes | 1992 | [235] |

textual data and extract multiword phrase frequency and analyze phrase proximity [124]. Data tomography tool is full-text co-word analysis which can use any key or index words, based upon computational linguistics and lexicography for research evaluation [125]. It assumes the frequencies with which phrases appear in documents are related to the main themes. This method cannot simply retrieve any type of large textual databases such as papers, reports, memos, and patents but also identify technical thrusts and themes and network among these areas [128]. This tool has four main processes as follows [130]:

- extract the text to be analyzed from source of databases
- identify the main themes of the text being analyzed
- determine the quantitative and qualitative relationships among the main themes and sub-themes
- track the evolution of these themes and their relationship over time.

One of the most unique characteristic in data tomography technique is a phase to utilize expert panel's decision to identify the appropriate information in disorganized data as well as to interpret the result [129]. Data tomography tool has

**Table 7** Data mining tools

| Approach | Characteristics | Inception | Reference |
|---|---|---|---|
| Data mining | - time-consuming<br>- relatively expensive<br>- appropriate for discontinuous technology forecasting | 1991 | [74] |
| Data Tomography | - multiword phrase frequency analysis<br>- phrase proximity analysis<br>- time-consuming<br>- identify promising/emerging research/ technology opportunities<br>- develop an independent R&D taxonomy | 1991 | [124, 125] |
| Text mining | - time-consuming<br>- relatively expensive<br>- appropriate for discontinuous technology forecasting | 1995 | [62] |
| Tech mining | - not restricted to mining abstract publication and patent records. It combines text and numerical data to best answer the questions | 2000 | [43] |

been applied many different fields to identify promising research opportunity and emerging technology areas [130].

In 1993, Alan Porter began to develop software and commercialized *VantagePoint* Software which was built upon ‘Technology Opportunities Analysis’ [181] approach in 2000 at Georgia Tech. It is a very powerful data mining tool, so called tech mining in his papers, for discovering knowledge in search results from patent and literature databases [179]. Tech mining combines text and numerical data to support technology management decision making and technology forecasting [44]. Tech mining, text mining of science and technology information resources, aims not only to analyze emerging technologies but to provide technology maturity, research trend and research network map [180] (Table 7).

- **Analogies; Comparison-based prediction**

By definition, analogy is typically defined as recognizable similarity or resemblance of form or function, but no logical connection or equivalence—as distinguished from a model. Forecasting by analogy attempts to predict possible futures by systematic comparison of the technology with similar one in a certain industry by looking at historical data. Analogies is a natural process using an intuitive thought based on similarities and is commonly used in inductive inference [153, 170]. Analogies are useful method but must be subservient to the general guidelines [212]. Thomas O’Connor provided insightful overview and various applications of analogies techniques in different field such as mythology, science, economics, politics, military, philosophy and religion [170].

Initial type of forecast by analogy is the use of growth curves to predict the advance of some technology, having growth curves that follow an S shape [133,

**Table 8** The characteristics of analogies

| Approach | Characteristics | Inception | Reference |
|---|---|---|---|
| Analogies | - easy to use<br>- the lack of integrated set of procedures<br>- deterministic<br>- intuitive and insightful method<br>- only work when relevant historical data is available<br>- not suitable for discontinuous technology | 1962 | [133, 160] |

151], since many technologies and products follow rapid growth stage and finally reach a constraint within a saturation level [3]. Martino identified four major challenges with analogies: lack of inherent necessity, historical uniqueness, historically conditioned awareness, and casual analogy [153]. He asserted these problems can be lessened by systematic method, which is that the technological change can be measured with regard to several different dimensions (technological, economic, managerial, political, social, cultural, intellectual, religious-ethical, and ecological) to compare two analogous situations. The key success factor of a forecast by analogy is to choose right technologies that are truly analogous to the one being forecast. Bright also highlights technological change should be systematically monitored to capture it [23] (Table 8).

- **Cross impact analysis (1966)**

Cross impact analysis is originally diversified from the scenario writing technique. It was first introduced for the Kaiser Aluminum Company by T. J. Gordon and O. Helmer at the Rand Corporation in 1966 [86]. Cross impact analysis was initially designed to eliminate some disadvantages of Delphi method which ignore potential relationship between the future events [84, 113]. This technique is the first attempt to assess the interaction of technological and social impacts for the purpose of interrelating intuitive forecasts by taking average likelihoods of occurrence for each event, considering time sequences, since most events and technology developments are associated with other events and technology developments in some senses. This tool provides useful means for analyzing the relationship between the factors. "Cross impact" coined by Olaf Helmer at the Rand Corporation means this relationship between events and technology developments [86]. It recognizes mutual effects such as the strength, direction and quality of interrelationship between events and technology developments from expert judgments [169]. This method attempts to gather forecasting information systematically for strategic decision making.

There are two major approaches for cross impact analysis [18]. One is INTERAX (Interactive Cross Impact Simulation) approach developed by S. Enzer at the Center for Futures Research (CFR) in the University of Southern California. INTERAX approach is to combine the advantages of trend impact analysis with strengths of cross impact analysis [105]. This tool involves analytic model which analyze evolutionary conditions and physical changes as well as expert's analysis

**Table 9** The types of cross impact analysis

| Approach | Characteristics | Inception | Reference |
|---|---|---|---|
| INTERAX | - using Monte Carlo random basis<br>- produce path scenario<br>- high start-up cost<br>- random selection of initial probabilities | 1966 | [57, 105, 160] |
| BASICS | - rapid input and editing of data<br>- long-range perspective<br>- numerous on-line sensitivity analysis<br>- static scenarios | 1977 | |

to describe social change and policy options in an interactive simulation [58]. The second thing is BASICS (Battelle Scenario Inputs to Corporate Strategies) approach mainly used by Battelle–Columbus Division in 1977. BASICS tool involves heuristic computations with no foundation in probability theory [26]. This approach is different from INTERAX in that it does not use Monte Carlo simulation, nor does it involve an independent forecast of the major variables [104] (Table 9).

- **System dynamics (1961)**

The System Dynamics method was first introduced by Jay Forrester at the MIT in 1961 [67, 68]. System Dynamics is an analytical approach to analyze dynamic behavior of complex social systems and to understand and influence how things change over time, based upon traditional management, cybernetic theories or feedback theory and computer simulation [70, 71, 160]. In 1968, its application expanded from corporate modeling to broader social systems [69]. There has been a variety of applications of System Dynamics in studying social, economic and environmental system behaviors and in analyzing policies [252].

With respect to technology forecasting application, System Dynamics is used not to predict the emergence of particular technologies, but to forecast future performance and system behavior or a pattern of variation of current system with no modification over a period of time [182]. System Dynamics is completely deterministic modeling focusing on causal connections, based on the assumption that the system of past development will hold in the future [87]. It requires causal assumptions and the existence of past or analogous data. This method is not quite appropriate as a forecasting tool in that every event certainly happens, forecasters already know how factors interrelate, and there is only one possible outcome [152, 160]. These characteristics do not reflect real word in technological change. Probabilistic System Dynamics is an attempt to overcome these disadvantages with stochastic events simulations from expert decisions [87, 225]. System Dynamics tool, however, has been more often used with other tools to forecast technological change [160].

System dynamics technique is a quantitative simulation approach illustrating qualitative variables extracted from written database as well as mental databases built up from experience and observation [70, 143, 182]. It is very useful technique in dealing with complex and nonlinear problems that may have side-effects, time delays and a series of interlocking feedback loop structures [67]. This method use computer modeling tool with various software packages such as DYSMAP[6] (Dynamic System Modelling and Analysis Package) [251], STELLA,[7] iThink,[8] Vensim,[9] and Powersim Studio.[10]

There is no crystal clear integrated set of procedures in System Dynamics modeling. Luna-Reyes and Andersen described 5 different System Dynamics modeling processes across the classic literature, varying from 3 to 7 different steps [143]. However, the 6-step process of system dynamics proposed by Jay Forrester is as follows [72]:

- Describe the system
- Convert description to level and rate equations
- Simulate the model
- Design alternative policies and structures
- Educate and debate.
- Implement changes in policies and structure.

System Dynamics model is an iterative process which has dynamic cause-and-effect feedback loops with a holistic view. Systems are typically described with diagram which has the links between stated variables indicated by arrows. Diagram can not only illustrate information flow and physical flow but easily understand the interrelationship between variables. The arrows represent both direction and plus or minus sign of influence between the different factors (positive or negative effect). The overall sign of the feedback loops are determined by the product of the signs on their constituent links (Table 10).

- **TFDEA (2001)**

Companies, governments, and other organizations are currently seeking ways to improve their operations. In this perspective, Data Envelopment Analysis (DEA) can provide the systematic process for evaluating alternatives, implementing strategies, and improving performance by benchmarking other decision making units (DMUs). DEA, as developed by Charnes et al. in 1978 and extended by Banker et al. (BCC) in 1984 is a linear programming procedure for a frontier

[6] DYSMAP was developed by the System Dynamics Group at Bradford Management Center.

[7] STELLA was introduced by isee systems (formerly High Performance Systems) in the late 1980s.

[8] isee systems (formerly High Performance Systems Inc.) in USA developed iThink for business simulation in 1990.

[9] Ventana Systems, Inc. created Vensim language and released Vensim in 1988.

[10] Powersim studio was developed Powersim Software AS, based in Bergen Norway.

**Table 10** The characteristics of system dynamics

| Approach | Characteristics | Inception | Reference |
|---|---|---|---|
| System dynamics | - useful in systemic thinking<br>- complex and time-consuming<br>- relatively providing clarity and unity<br>- the lack of integrated set of procedures<br>- real world not always cyclical having feedback loop<br>- deterministic<br>- not suitable for discontinuous technology | 1961 | [143, 152, 160, 190] |

analysis of inputs and outputs [75]. There are a lot of theoretical and empirical study extensions that have appeared in literature. Benchmarking core technology performance and Product trend with DEA offers an effective means to determine technological capability over time as well as component development time without the burden of fixed a priori weighting schemas. Also it provides clear understanding key characteristics to forecast technology trend by using benchmarking other companies as fast-followers.

In this viewpoint, since its inception in 2001, Technology Forecasting using DEA (TFDEA) method can provide quite a bit implementable tool to decision makers by bridging the gap between well-established management science methodology so called Data Envelopment Analysis and Technology Forecasting field. This method is to measure the technological rate of change in order to forecast future technological advance. There are already some case studies to validate the method usability applied to a variety of industries including enterprise database systems, microprocessors, hard disk drives, portable flash storage, fighter jet and Turbofan Jet Engines [5, 106, 107]. TFDEA technique provides more accurate result than multiple regression models in some cases (Table 11).

## E. **Normative forecasting methods**

Normative technology forecasting methods screen technology transfer by running against its movement [111]. Normative forecasting similarly forced forecasters to consider complex social systems that resisted reductionism with its simplified models based upon system analysis [137, 153]. Normative approach considers objectives, needs, and future desires as basic elements for forecasts and identifies constraints. Following description of each technology forecasting methods attempt to provide a basic knowledge for its practical applications.

- **Relevance trees (1963)**

**Table 11** The characteristics of TFDEA

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| TFDEA | - restrospective<br>- not robust<br>- not applicable for discontinuous technology<br>- needs conjunction with complementary methods in some cases | 2001 | [4] |

The relevance trees are one of the most traditional normative technology forecasting methods. The concept of relevance trees linked with decision making was first addressed in 1957 by C. W. Churchman et al. in their introductory operation research book [37]. Qualitative relevance trees were first designed to aid decision making process [37, 153]. The structure of relevance tree is very similar to that of ordinary decision tree. Thereafter, quantitative relevance tree techniques were pioneered by the PATTERN (Planning Assistance Through Technical Evaluation of Relevance Numbers) scheme which was first applied to military and space activity program in large scale by Honeywell's Military and Space Sciences Department in 1963, refined and extended to all military and space activities in which Honeywell have interest in 1964 [111, 150]. Furthermore, this method was applied extensively to NASA's Apollo Payload Evaluation, US Air Force, and private advertising company [111].

In essence, the relevance tree technique involves the drawing of hierarchical structure of the technological problems that must be resolved to meet the goals which are at the upper level. The head end of the tree is the final objective of a proposed technology. The hierarchical tree diagrams which has branches and nodes should be deployed by the principle of mutual exclusiveness and collective exhaustiveness [153]. It is prerequisite that forecasters form the hierarchical structure and identify all related factors of technology development. Graphical tree format of relevance trees is very easy to understand various future achievements and relationships among them. Relevance trees can be very useful and powerful tool to identify all problems and solutions and break the performance requirements down for a specific technology in order to achieve some overall objective [111, 153]. In addition, the numerical analysis of relevance trees incorporating relevance numbers is a systematic approach to assess probabilities of solutions to meet the goals and objectives of significant social problems [135, 153]. The probabilities can be interpreted as the likelihood of achieving the future needs and objectives of individual technology (Table 12).

- **AHP (Analytic hierarchy process, early 1970s); Multi-criteria decision model**

Analytical Hierarchy Process (AHP) is a method that uses criteria and pair-wise comparisons between the criteria to ascertain the relative importance of each with

**Table 12** The characteristics of relevance tree

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| Relevance tree | - The hierarchical structure of technology development must be known<br>- applicable for discontinuous/continuous technology<br>- useful for areas of fundamental research<br>- applicable to the guidance of fundamental research contributing to social goals | 1963 | [111, 153] |

respect to each other. Since Thomas L. Saaty introduced AHP method in [230], it has widely been accepted as a technique to prioritize the elemental issues in complex problems in decision making process with the various applications of forecasting, selection, evaluation, Benefit-Cost analysis, allocations, planning and development, priority and ranking [238]. Regarding AHP application within academia, AHP has been utilized within manufacturing, environmental managements and agriculture, transportation, power and energy, healthcare, the construction industry, R&D, education, e-business and various fields.

Even though technology forecasting using AHP provides an opportunity to contain the tangible as well as non-tangible elements, and the capability to develop environmental factors [122], there are few application literatures discussing the technology forecasting using AHP method. AHP was employed in forecasting the technological capabilities with growth curves [122]. Recently, this technique was applied to as a part of the technology roadmapping framework [79].

AHP method analyzes the hierarchical structure of a future technology and measures the relative importance among the classified element technologies affecting the development process of the technology. Weights and inconsistencies are found based upon algebraic methods and are utilized to apply scores to each decision alternative. Thus, the decision alternative with the highest score should be chosen [103]. By comparing the individual pairs of criteria, these models provide an ability to compare an issue with regards to each immediately higher level. This in turn allows a relative importance to be determined by the decision-maker. A pair-wise comparison, comparing each pair at a time in the corresponding level, is employed to estimate major factors on numerical scale (1–9).

However, AHP does have some limitations and advantages. The "major issue" with AHP is the accuracy of the weightings leading the paradigm to be "essentially qualitative and not realistically quantitative." On the other hand, it helps to reach a group consensus in a quantitative manner (Table 13).

- **Morphological analysis (1942)**

J.W. von Goethe (1749–1832) introduced the term of *"Morphology"* to denote the principles of formation and transformation of organic bodies. This early theoretical morphology was eclipsed by Darwinnian evolutionary theory in late 19C. Goethe initially provided methodological type-concept in his conception of morphotypes

**Table 13** The characteristics of AHP

| Characteristics | Advantage | Disadvantage | Inception | Reference |
|---|---|---|---|---|
| - qualitative as well as quantitative<br>- subjective judgments<br>- evaluation of alternatives<br>- applicable for discontinuous/ continuous technology | - group consensus<br>- easy-to-understand<br>- software support available | - accuracy of the weightings<br>- rank reversals are possible<br>- large number of pair-wise comparisons required | Early 1970s | [51, 230, 204–205] |

[244]. However, Max Weber simplified, generalized and popularized typology analysis as a simple concept-structuring method applicable to virtually any area of investigation [195]. Morphological analysis (MA) was coined by Fritz Zwicky, a Swiss astrophysicist and aerospace scientist, who was using the method in 1942, and who propagated it by founding a Society for Morphological Research [250].

Morphology technique is used to analyze the structure of problems and to derive the performance requirements for individual element among the remaining solutions for normative technology forecasting [153]. MA is concerned with the structure and arrangement of parts of an object, and how these conform to create a whole or Gestalt [195]. MA is a tool to structure problems rather than solve them [250]. MA can be useful technique to find new relationship or configurations not so evident.

This method has been not only extended to the areas of policy analysis and future studies, but also computerized to structure and analyze intricate policy issues, develop future scenarios and model strategy alternative [192, 194]. In 1995, Tom Ritchey, the founder of the Swedish Morphological Society, and others first developed Casper software which is advanced computer support for MA at the Institution for Technology Foresight and Assessment at the Swedish Defense Research Agency [193]. Thereafter, they had upgraded Casper to a leading proprietary software system, so called Carma™ (Computer-Aided Resource for Morphological Analysis) for general morphological analysis for the past 10 years [194, 229] (Table 14).

- **Backcasting (1974)**

Backcasting is one of the normative technology future analysis methods which involves setting policy goal at first and then determining how those goals could be reached from desirable future to the present [232]. Backcasting approach can be complementary to technology forecasting tools [101]. Backcasting is not intended to indicate what the future will likely be, based on the probability, but to indicate the relative feasibility and implications of different policy goals and alternative future on the basis other criteria like scenario approach [199]. This method, called ‘backward-looking analysis’ at that time, was first developed by Amory B. Lovins in an analysis of Japanese electricity supply and demand futures, employing variants of an alternative method in 1974, and then, Robinson introduced first

**Table 14** The characteristics of morphological analysis

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| Morphological analysis | - structuring and investigating the total set of relationships contained in multi-dimensional, usually non-quantifiable, problem complexes<br>- qualitative<br>- complementary method for relevance tree<br>- combining with scenario method<br>- applicable for discontinuous/continuous technology<br>- relatively traceable and even reproducible | 1942 | [153, 192, 250] |

'backcasting' terminology in [199]. Historically, this method has the same origin as the strategic and multiple scenario approaches which was popularized by Shell in the early 1970s during the first oil price crisis [186].

Backcasting has been mainly applied in energy planning field and extended to transportation, governmental program for sustainable technology development and technology future analysis in Canada, Sweden, UK and Netherland [186–233, 202]. Backcasting technique adopts a scenario approach in order to identify possible alternatives and to analyze consequences and conditions for these futures to be achieved [200]. Backcasting studies develop images of the future or scenario that attain the goals addressed in the vision. In essence, the backcasting approach involves three major elements [110]: (i) Defining a long term objectives and goals followed by (ii) Developing a short term approach resulting into (iii) Implementation requirements of a research and development agenda. Recently, participatory backcasting approach has gained more popularity in implementation of this technique [187]. It is very vital to understand the culture, interests and motives of stakeholders in practice of it (Table 15).

F. **Normative/Explorative technology forecasting**

- **Delphi method (early 1950)**

The Delphi method is one of the oldest techniques of eliciting responses and refining expert group decisions [46]. Olaf Helmer et al. at RAND Corporation, established in 1947 by the US Air Force, developed the Delphi method in the early 1950s, which was designed to remove conference room impediments to a more structured expert consensus [138]. The Delphi technique is to integrate subjective expert opinions with respect to the likelihood of realizing uncertain future technology, the probable development date, desirability, etc. Helmer and Rescher set out the philosophical backdrop for Delphi and set limits of expectation about what can and cannot be known when the questions being addressed fall into the category of "inexact science." [98]. The major series of experiments of Delphi were performed at the RAND Corporation to evaluate the procedures [47].

Delphi has gained its popularity due to easy implementation and facilitation of group discussions. A variety of technology forecasting and national technology foresight studies mainly use Delphi technique with the participation of hundreds or thousands experts [94]. It can provide a more feasible forecast in terms of emerging technology and long range (20–30 years) planning, if trend analysis based on historical quantitative data is not possible. Typically this technique

**Table 15** The characteristics of backcasting

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| Backcasting | - better suited for long-term problems<br>- interactive and iterative between future visions and present actions<br>- participatory approach<br>- incorporate discontinuous/continuous technology<br>- explicitly normative and design-oriented | 1974 | [186, 187, 199, 200] |

involves new emerging technology and ethical or moral considerations, when expert opinion is only available source of the prediction of technological change. Moreover, expert opinions are needed, when external factors such as decisions of sponsors and opponents of the technology, and changes in public opinion are dominant [153].

The Delphi process has two distinct forms such as conventional Delphi and Delphi Conference [138]. Delphi process consists of preparation, consecutive survey with 2–6 iterations until a general consensus of the outcome is reached, analysis and implementation. It provides the results of each round so that experts may change their previous assessments to the same questions. This method fundamentally relies on the knowledge, experience and judgments of quality of the expert panels. The size of expert panel in Delphi basically depends on the number of issues. A large number of respondents appear to be better performed to treat adequately some issue, but the groups with eleven or seven participants are more effective in forecasting than larger groups in Brockhoff's study of Delphi performance [138]. Delphi process gives the participants objective feedback from structured group consensus. The basic procedures of Delphi methods [35, 47, 153, 160]:

- Identify goals of the study and requirements
- Structure the questionnaire with scale or open-ended answer to support study goals
- Identify the experts in each field
- Anonymous response
- Iteration (2–6 times, 3 or 4 as usual)
- Controlled feedback
- Statistical group response. ($\aleph^2$test, median and upper and lower quartiles for review)
- Present the consensus forecast.

It is critical to control carefully a series of intensive questionnaires and feedback between rounds. Panel opinion is accepted as a relevant aggregate of individual estimates on the final round (Table 16).

**Table 16** The characteristics of Delphi

| Characteristics | Advantage | Disadvantage | Inception | Reference |
|---|---|---|---|---|
| - exhibit bipolar views not forcing consensus<br>- foster the better use of group interaction<br>- qualitative approach<br>- subjective | - the possible participation of a diverse experts in disparate geographical areas<br>- forced consensus | - idiosyncratic<br>- time consuming<br>- forced consensus<br>- relatively expensive<br>- biases of expert decisions<br>- little control over participants | Early 1950s | [94, 153, 160] |

- **Nominal group technique (1968)**

The nominal Group technique (NGT) was introduced by Delbecq et al. in 1975 as an organizational planning tool [50]. The nominal group is illustrated as a group in which each panel expert work in the presence of others but do not verbally interact [49]. There is no preliminary discussion in NGT. NGT is designed to remove the problems of group interaction. NGT has a similarity to Delphi method using expert panels. In contrast to the Delphi method, NGT not merely holds effectively structured meetings facilitated by a third party moderator, but also involves efficient discussion among participants concerning each expert's initial opinion [135]. NGT is very efficiently structured process for idea generation and group consensus in terms of particular issues [221]. NGT allows bandwagon effect of majority such that the group leader or a strong expert may affect the panel consensus with limited range by prioritization using secret ballot during discussion of vote phase. So, it is of vital significance to select experts carefully in order to remove this disadvantage in the NGT. There are two types of group idea generation process in NGT: intra-organizational group decision making and soliciting expert or citizen views as input for public policy formulation [38].
The NGT has been mainly used for participatory problem solving approach by group analytical decision making in social science field [49] and extended the application to almost any problem and field such as health care studies [158, 243–203], social service [201], consumer research [38], new product development [25], and information system [99]. The final output in NGT is a rank-ordered list of new ideas assessed by expert panels with the number of points which account for the level of consensus. The 6-step process of group idea generation and prioritization in the NGT is as follows:

- Introduction of the task statement
- Individual, silent generation of ideas
- Round robin listing of ideas
- Clarification of ideas
- Consolidation of ideas
- Voting and ranking of ideas by secret ballot.

- **Scenario Planning/Writing (1950s)**

Scenario planning has gained its popularity in technology forecasting methods and decision making in the face of uncertainty. It formally started from the use of computer simulation to measure probabilities of the atmosphere and planet catching fire in the Manhattan project in 1942 [213]. The Rand Corporation also mainly introduced scenario planning for US military purpose by Herman Kahn in 1950s, based on the previous groundwork of computer simulation, game theory, and war games [114]. Furthermore, private companies such as Royal Dutch/Shell and GE developed scenario planning technique for corporate strategic planning in the late 1960 and early 1970s [18, 160, 245]. For an instance, Shell's adequate and

**Table 17** The characteristics of Nominal Group Technique

| Characteristics | Advantage | Disadvantage | Inception | Reference |
|---|---|---|---|---|
| - qualitative approach<br>- alternative to Delphi method<br>- information shared<br>- involve intensive discussion<br>- aims at panel consensus<br>- applicable to wide variety of areas | - participation of all members<br>- minimizing group "noise"<br>- structure, collects many creative ideas<br>- easy to learn<br>- easy to integrate into programs and projects of larger scope<br>- intra- and intergroup comparisons are possible | - overly mechanical or simplified<br>- structure does not allow for interaction of ideas | 1968 | [38, 50, 160, 135, 221] |

timely reaction to the oil crisis in 1973 drew attention to the scenario analysis [245, 246] (Table 17).

Kahn and Wiener, pioneers in scenario planning, first defined scenario as "hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision-points" [115]. Scenario can be simply regarded as a series of events that expert imagine plausible future occurrence. Schoemaker illustrated scenario planning as "a disciplined method for imagining possible futures in which organizational decisions may be played out" [214]. Scenario planning is the use of internally consistent narrative descriptions of particular sets of events, diverse possible situations or developments in the future. It explores the future to identify that multiple outcomes can occur. In essence, scenario planning is a systemic approach to create alternative, dynamic stories about many plausible futures in complex and uncertain business environments rather than to focus on a possible single outcome [216]. It explores the joint impact and implications of various different ends. This technique is useful in drastically changing environments including disruptive technologies.

Scenario planning can be classified variously based on different aspects of it such as project topic, process design, time and etc. [156, 241]. There are, however, two kinds of distinct scenario approaches with respect to technology forecasting: projective (descriptive) and prospective (normative, prescriptive) [16, 80, 241]. Projective scenarios explore possible future images from current situations like future forward. They describe what can happen. On the contrary, prospective scenarios describe probable or preferable futures on the basis of different visions of the future. They write scenarios how to reach several significant objectives like backcasting.

Theoretical foundations of scenario planning are relatively not solid [216, 239]. In practice, however, there has been a variety of applications of scenario planning in diverse fields such as energy, electronics, aircraft, telecommunication,

**Table 18** The summary of three approaches of scenario planning

| Types | Characteristics | Inception | Reference |
|---|---|---|---|
| Intuitive logics | - developed by shell<br>- appropriate for short-term forecast<br>- restrict the diversity of the constructed scenarios | Late 1960s | [105, 246] |
| Trend impact analysis | - employed by the Future Group<br>- a combination of statistical extrapolations with probabilities | Early 1970s | [105] |
| Cross-impact analysis | - practiced by Battelle with BASICS (Batelle Scenario Inputs to Corporate Strategies) and the center for Futures Research (INTERAX)<br>- a highly formalized method | 1966 | [105, 160] |

healthcare and environment industry [134, 156, 159–220]. So, there has been distinctively three forms of scenario planning implemented in real business world [105]. In this section, I only shed light on 'Intuitive Logics' tool typically introduced by Pierre Wack, a planner at Shell Francaise [245, 246], since the other two approaches, trend impact analysis and cross impact analysis, are described in detail at other sections. 'Intuitive Logics' was mainly used by SRI International, Global Business Network, and Shell [105]. The intuitive logic approach considers a complex set of relationships to make a better decision among STEEP headings (social, technological, economic, environmental, and political) factors which are external environment to organization [105]. This method involves a series of intuitive logics generated by expert communication and analysis without depending on a complex computer simulation model [104]. This approach depends strongly on participants' intuition and communication skills of the expert panels [156] (Table 18).

Scenario developers must be experts in all aspects of the proposed technology to seek out better decision. "They answer two types of questions: (a) precisely how might some hypothetical situation come about, step by step? and (b) what alternatives exist, for each actor, at each step, for preventing, diverting, or facilitating the process?" [153].

The basic procedures of scenario writing is as follows [73, 105]:

- Identifying the decisions and strategic concerns
- Analyzing major appropriate factors (internal and external environmental forces; social, technological, economic, political, competition)
- Elaborate the assumptions to be implicit in the scenario logics with its scope
- Identify related sources of information for major factors
- Analyze the issues/points of divergence resulting from conflicting factors in the current situation

- Consolidate the information and predictions obtained to develop internally coherent pictures or development pathway
- Analyzing implications for decisions and strategies.

| Characteristics | Advantage | Disadvantage | Inception | Reference |
|---|---|---|---|---|
| - manpower intensive<br>- embrace qualitative perspectives, quantitative data, and macroscopic factors<br>- tend to be broad and conceptual rather than specific | - very flexible<br>- incorporate discontinuous technology or disruptive events | - can be too qualitative<br>- relatively expensive<br>- time-consuming | 1950s | [114, 160]<br>[156, 211] |

- **Trend impact analysis (early 1970s)**

Trend impact analysis was incepted in the early 1970s, diversified from the scenario planning tool [88]. This method was mainly used to add quantification to a scenario by The Futures Group consulting firm. It is primarily descriptive approach evolved from the traditional forecasting tools, on the basis of extrapolating historical data with no consideration of unprecedented future situations [18]. This tool aims to enhance the accuracy and usability of approaches to trend extrapolation. Trend impact analysis not only collects past data and projects this to generate ‘surprise-free’ future trends, but also employ expert judgment tool to seek the possibility of occurrence and its future impact in terms of unprecedented events [85]. This technique, in other words, provides a systematic means for combining both statistical extrapolations and expert judgments to identify a set of future situations. The critical part of this tool is to estimate the magnitude of impact at each extraordinary event on the trend from experts’ decisions such as the largest impact or the steady-state impact and beginning time of unusual trend [85]. It captures the product of probabilities and impacts in selected significant situations the forecasters can focus on in an efficient manner.

On the comparison with cross-impact analysis, trend impact analysis just renders an independent forecast of the key dependent variable, with no consideration of evaluation of possible combination of each event [105]. It also need to use cross-impact technique to calculate the probability of impacts of coupled events [85]. Further this technique requires long past data for extrapolating trends. For these reason, it is not popular method among forecasters. Trend impact analysis consists of typical five steps as follows [104]:

- Collecting time-series past data
- Generating a surprise-free extrapolation
- Establishing probabilities of events occurring over time
- Adjusting extrapolation
- Writing Scenario from at least two of the forecasts.

- **Technology roadmapping (late 1970s)**

Technology roadmapping was first used by Corning and Motorola to build up corporate and business strategy in the late 1970s [184]. Motorola popularized its own technology roadmap which has a single layer roadmap, focusing on the technological evolution associated with a product and it's features as a business planning tool in [248]. Technology roadmap is a useful tool for managing R&D planning as well as identifying the future of technological progress. Robert Galvin, former Motorola chairman, defines technology roadmap as "an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field" [76]. Technology roadmap is mainly developed for three purposes: technology forecasting, planning and communication. Technology roadmapping, in other words, attempts to reveal a specific characteristic or an attribute of technology development over designated future time. It is also an effective tool for technology planning and communication which fits within a broader set of business planning [20, 175]. Finally, this method provides a useful means for the communication between design & development engineers and marketing personnel which technologies will be required in future products. Technology roadmapping technique has gained significant and subsequent acceptance within corporations [1–10, 92, 248], across industries [9–77, 95, 109], and national foresights [206] (Table 19).

Technology Roadmapping typically takes a retrospective (top-down) approach which backwardly illustrates how to accomplish a given target from decades past to the present or a prospective (bottom up) approach which looks forward from the present to the future and also has combination form of them [127]. Most of technology roadmaps, however, involve prospective process which has two different types analysis: market pull and technology push [127, 176]. The prospective approach is typically employed in technology forecasting. In addition, there is no standardized roadmapping process to generate roadmaps [177]. It differs based upon the business objectives, product and service types, available resources, and knowledge and information, etc. [247].

There are three major questions to develop technology roadmap [174]: (Table 20)

- Where does a company want to go?
- Where is a company now?
- How can a company reach its target?

**Table 19** The characteristics of Trend Impact Analysis

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| Trend impact analysis | - relatively simple and easy to use<br>- require long historical data for time-series analysis or causal methods<br>- ensure internal consistency<br>- provide probable range of possible situations<br>- well suited for policy evaluation<br>- partially applicable to disruptive technology | Early 1970s | [18, 85, 88] |

**Table 20** The characteristics of Technology Roadmapping

| Type | Characteristics | Inception | Reference |
|---|---|---|---|
| Technology Roadmapping | - relatively expensive<br>- exploratory/normative forecasting tool<br>- subjective excercise<br>- not much applicable to disruptive technology but there are some attempts combining with other techniques | Late 1970s | [126, 118–139, 184, 248] |

## 3 Analysis of the Relationship Among TF Methods

In this section, this study aims to analyze the historical relation between normative and exploratory methods in literatures and identify the methodological linkages among them. Some technology forecasting methods are tightly employed together to predict the technological change or innovations, but others are not. It is, however, theoretically inappropriate to use composite methods among them in order to solve practical forecasting problems, in case of that it has the conflict of assumptions based on them. Furthermore, the selection of proper technology forecasting methods depends on the nature of the technologies [161]. Therefore it requires experience and expertise in various TF techniques to select the appropriate forecasting models. This paper categorizes technology forecasting techniques according to exploratory and normative approaches. This paper analyzes the applicability of technology characteristics such as disruptive/discontinuous and continuous technology. Figure 1 shows a matrix of technology forecasting

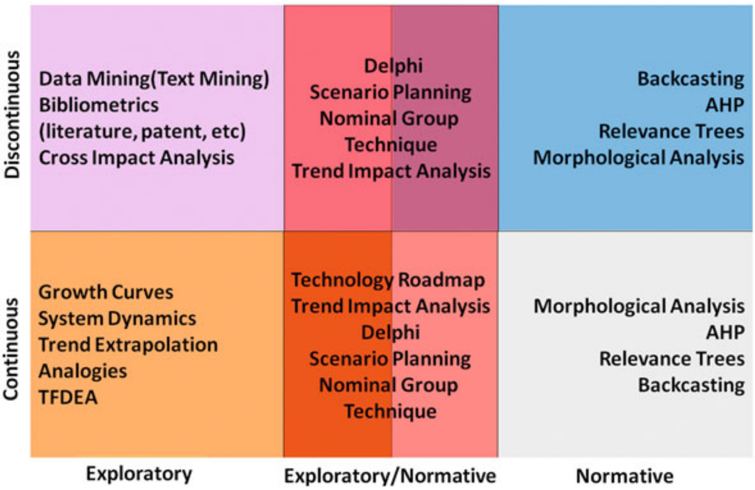


**Fig. 1** A matrix of technology forecasting tools

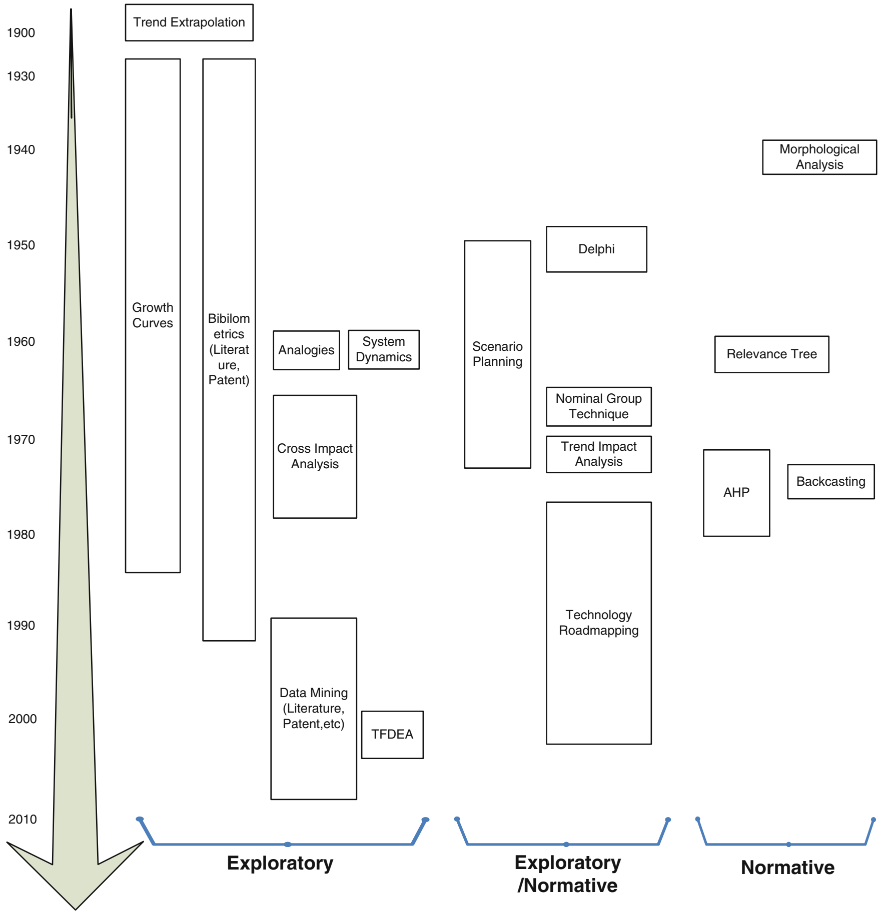


**Fig. 2** The chronological tree of technology forecasting techniques

methods by type of techniques and technological characteristics. Within each cell, TF methods are listed in descending order of frequent and effective uses.

Methodologies in technology foresight and technology forecasting are not fixed, a combination of different approaches and methods are required to improve the accuracy of forecasting. Hybrid methods, combinations of different forecasting methods, are superior to forecasts based on a single method [212]. A combination of multiple techniques enables forecasters to analyze various perspectives (organizational, technology, personal, social, and environmental) [45]. The famous experts in TF argue that complexity science and rapid social change required the need for emerging tools and combined forecasting methods with exploratory as well as normative techniques [41]. During the last four decades, especially after the emergence of Information and Communication Technology (ICT), some of the different approaches using much information like patents, journals, and research

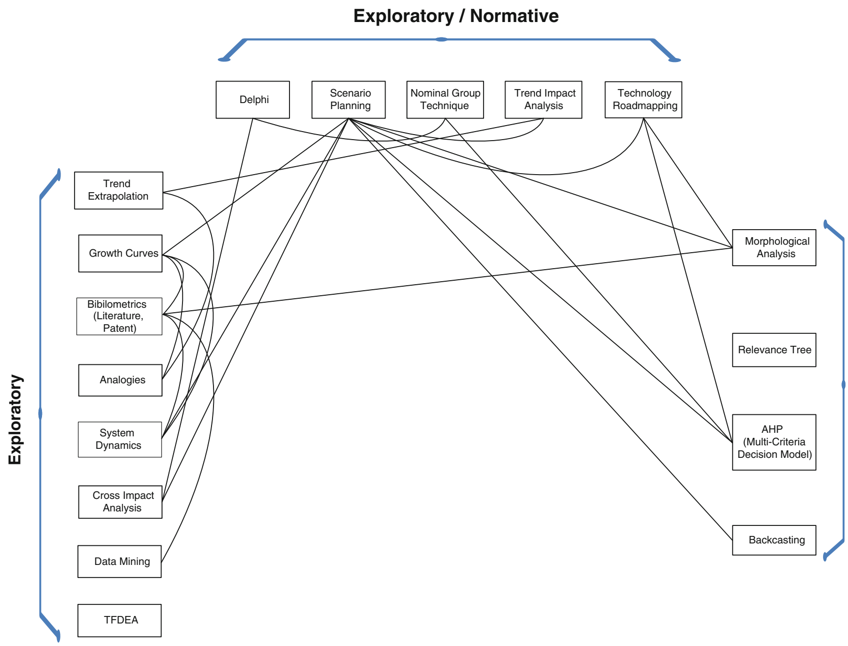


**Fig. 3** The correlation map among TF techniques

awards, have been continuously developed by different researchers combing with many other tools. Figure 2 presents the chronological tree of TF methods in a timely mannered way.

There are a number of papers to combine with other TF tools in order to offset weaknesses of one forecasting technique such as technology roadmapping with scenario technique [226], Delphi with cross impact analysis [56], Bibliometric with growth curves and system dynamics [45], and technology roadmapping with morphological analysis and text mining [253], etc. This study identifies research method linkage for technology forecasting through literatures review. Figure 3 presents the correlation between TF methods. Some articles combine the exploratory and the normative approaches to TF. Most of linkages are related with between exploratory and exploratory/normative methods or normative and exploratory/normative techniques. Furthermore, there are a few direct linkages between normative and exploratory methods, just except the combination of text mining and morphological analysis. These characteristics of relationship among TF methods reflect similarities in assumptions as well as methodological backgrounds among them. Research gap can be found in the correlation map among TF techniques.

## 4 Conclusions

This paper starts with an introduction to technology forecasting in historical overview and analyze some characteristics, advantage/disadvantage, origins and chronological evolution in a variety of TF methods. Finally, the study ends with some evolutionary figure not only to identify research gap but to select applicable and practical technology forecasting methods for future study in terms of different field like bio-medical device. Further researches are needed to survey the efficiency and effectiveness of combined methods in order to compare outputs in this paper. Text mining or co-word analysis in literatures of composite TF techniques leads to future research to analyze quantitatively the relationship among TF methods. Lastly, more comprehensive reviews which include econometric, correlation method, causal model, simulation and TRIZ, etc. would be a good benefit for this analysis. In summary, this study provides an informative summary of technology forecasting methods for the researchers and practitioners for their future work. New approaches with different combination of TF tools would be open to all forecasters.

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# Use of Multiple Perspectives and Decision Modeling for Solar Photovoltaic Technology Assessment

**Nasir J. Sheikh and Tugrul Daim**

**Abstract** As global warming and foreign oil dependence debates grow, more organizations are evaluating renewable energy. Renewable energy generation technologies are complex systems that have wide-ranging implications in their production and deployment. Using multiple perspectives such as social, technological, economic, environmental, and political (STEEP) and their decomposition into multiple criteria or indicators provide a broader yet explicit assessment of the technology under consideration. An effective method of determining the relative importance of a criterion with respect to others is by hierarchical decision modeling and expert judgment quantification instruments. These combined approaches can improve decision making for technology assessment and selection. This paper describes the approach through an example for photovoltaic solar technologies.

## 1 Introduction

Policies at national and international level are being implemented to incent and support the growth of renewable energy for a variety of reasons including climate change mitigation, fossil fuel pricing, societal demand, and renewable energy pricing heading towards grid parity [1, 3, 4, 17].

Energy technology and deployment planning efforts include energy sourcing and the evaluation of energy conversion devices to meet the desired energy demands in a relative optimal fashion. In today's world an energy planning decision involves a complex process of weighing and balancing diverse socio-political, technical,

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economic, and environmental dimensions or perspectives with spatial and temporal considerations. This balancing act is becoming increasing important as nations and peoples are becoming more aware of their rights as responsible citizens and their responsibilities as preservers of the social and natural environments. These dimensions or perspectives are usually represented as multiple criteria (and may include sub-criteria) and may represent conflicting or opposing objectives. These criteria may sometimes be difficult to define and may include quantitative and qualitative sub-criteria or factors [7]. Decision making around energy planning using multiple criteria analysis has been in use for over forty years [19, 24, 27]. Up to the 1970s the most popular criteria was cost, however in the 1980s environmental considerations also became important. Later social aspects were incorporated in the decision analysis and planning process. Political criteria also began to be explicitly recognized through public policies and regulations. Adding to the complexity, renewable energy sources brought further sets of nuances and criteria. This also broadened the scope of evaluations and decision making.

In terms of technology options, these too have increased significantly due to the increase in research and development (R&D) in renewable energy technologies [20, 9, 21]. Public and private sector decision makers now need to assess technologies with respect to a whole range of perspectives and criteria. Better methods are needed for decisions on renewable energy especially since the effect of such technology decisions will be felt for the life of the technology which could easily exceed fifteen to twenty years.

## 2 Multiple Perspectives and Decision Making

Prior research demonstrated the use of multiple perspectives in many different areas [12–15]. The fundamental concepts can be expanded to be applicable for renewable energy technologies, systems, and processes.

In this paper these renewable energy multiple perspectives are referred to as: social, technological, economic, environmental, and political (STEEP). These perspectives are composed of multiple criteria and each criteria in-turn is composed of multiple sub-criteria (and may be referred to as "factors" for easy distinction). The criteria that relates to each perspective can be stated as follows:

- ***Social Perspective.*** Criteria or factors that impact society—positively or negatively
- ***Technical or Technological Perspective.*** Criteria or factors that relate to technical performance
- ***Economic Perspective.*** Criteria or factors that are indicated by cost of technology diffusion, market adoption, and life-cycle costs ("push–pull-sustenance")
- ***Environmental Perspective.*** Criteria or factors that have an impact on the environment and the earth's natural ecosystems

- ***Political Perspective.*** Criteria or factors that make up political motivation, policies and regulations, market special interests, compliance, and security.

Despite the growing need for energy multiple perspectives, a literature review indicates that studies and findings are limited in scope, cover broad criteria (and not specifics related to renewable energy), have limited capability for operationalization, are project or policy oriented, and have almost no reference to specific renewable energy technologies (especially solar photovoltaic technologies) [29]. Considering all five perspectives for decision modeling and technology assessments in the area of renewable energy generation is a new area of research and may prove to be more effective than using their subset.

A variety of decision making and support tools and methods have been used by energy planners and decision makers for planning, project selection, environmental, and social impact. Reviewing journal literature on energy decision model indicates that the most popular model used is Analytic Hierarchy Process (AHP—a hierarchical decision model) developed by Thomas Saaty [2, 5, 6, 11, 12, 16, 18, 23, 25, 26, 28, 30, 31, 32]. AHP is the most well-known hierarchical decision model (HDM). The HDM model lends itself easily to a layered approach of ranking and prioritizing perspectives and their associated criteria and sub-criteria. Another HDM model developed by Dundar Kocaoglu is utilized by the author for this research [10]. The results from using this HDM model will be very similar to those from AHP.

## 3 Solar Photovoltaics: Trends

Market research indicates a high growth rate of solar photovoltaic (PV) deployments [8]. The cumulative positive affect of factors such net metering rules, electric rate tariff levels and structures, availability of financial incentives, system pricing, and carbon legislation are evident and will continue to spur growth in PV adoption [22]. [It should be noted that storage and distribution of PV generated electricity is agnostic to solar energy generation technologies].

## 4 Problem Statement

A comprehensive renewable energy technologies assessment is generally a complex decision problem since there are multiple perspectives (such as the five perspectives referred to earlier) to consider. This complex decision problem can be decomposed or formulated as an analytical hierarchical decision model (HDM) where different perspectives and their associated criteria can be prioritized or ranked. The selection of various levels of criteria (or constraints) can then be applied to address the question, “In the judgment of the decision makers and experts which perspective or criteria are more important than others?" For the purpose of this research, focus is on solar photovoltaic renewable energy technologies.

This is part of ongoing research at the Research Institute for Sustainable Energy (RISE), Department of Engineering and Technology Management, Portland State University, Oregon. The program includes use of HDM for evaluation of criteria, use of desirability functions (similar to utility function) for evaluation of factors, and then technology characterization as a composite of perspectives, criteria, and factors.

## 5 Methodology

As stated in the problem statement the selected methodology involves an analytical decision model that captures the judgment of the market experts and company's management and subject matter experts.

In effect, the methodology consists of four parts:

- Decision modeling process: building the analytical hierarchical decision Model
- Selecting an expert panel
- Design of judgment quantification instrument (survey questionnaire)
- Expert panel survey.

The decision model with objectives and criteria can be utilized (as a decision tool) to provide direction for the stated problem or decision making.

A *panel* of experts is selected to assist in model development and pair-wise comparison of the perspectives and criteria. The criteria are composed of sub-criteria named as "factors". Experience indicates that 10–15 experts can provide reasonable and balanced results. The experts can have different worldviews or philosophical frames of reference which can heavily influence the results. Hence different strategies can be developed based on the worldviews. These worldviews include (but are not limited to):

- Technology supplier or developer
- Power utility or service provider
- Government policy maker.

### *5.1 Decision Modeling Process*

The decision model is developed by first setting the mission and perspectives for the model and the criteria that would be used to select the most desired target market. This is depicted in Fig. 1.

As mentioned earlier, considering this to be a test case, only the initial results were analyzed.

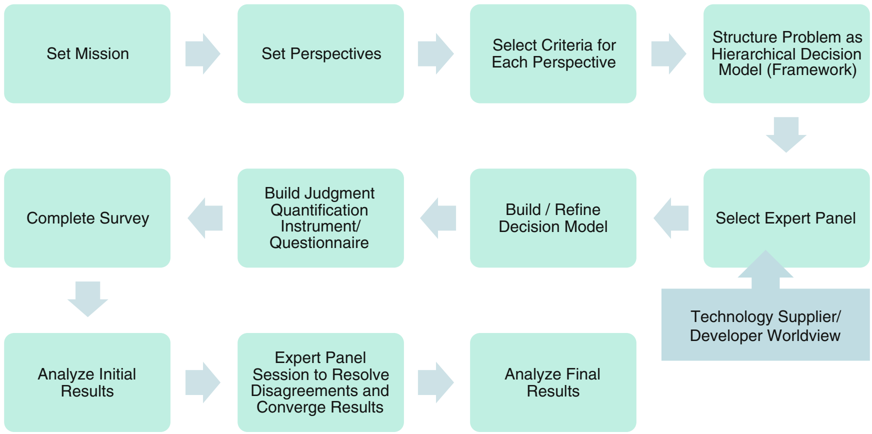


**Fig. 1** Decision modeling process

### 5.1.1 Defining the Hierarchical Decision Model

The objectives, criteria, and sub-criteria (called factors) consisted of the following:

- ***Overall Objective or Mission.*** The ultimate goal of the decision model is to help with a comprehensive assessment of photovoltaic technologies.
- ***STEEP Perspectives.*** To fulfill the mission these five perspectives or dimensions were considered important. These may also be important consideration for worldviews of a technology supplier/developer, power utility or service provider, or government policy maker.
- ***Criteria for Each STEEP Perspective.*** The important criteria or constraints for each objective are listed in Table 1 below as:

Each criterion is composed of multiple sub-criteria or factors. These are listed in Appendix A: Multiple Criteria and Factors for STEEP Perspectives are developed mainly from a literature review [29].

- ***HDM Model.*** The HDM model is shown in Fig 2 and includes the relations between mission, perspectives, and criteria. An enlarged version of this model is shown in Appendix A: Hierarchical Decision Model.

## 6 Results and Analysis

A group of professional with experience in this area was consulted to quantify the model in this case. The results need to be viewed with demonstration purpose and should not be used to make a decision on these technologies. The objective of this papaer is to demonstrate how to build an evaluation model.

**Table 1** Multiple criteria for each STEEP perspective (derived from [29] and expert opinions)

| Social | Technical | Economic | Environmental | Political |
|---|---|---|---|---|
| Public perception | Efficiency | Product costs | Pollution/negative impact | Policies |
| Employment | Technology maturity | LCOE (Electricity generation costs) | Environmental benefits/ positive impact | Regulation/ deregulation of power markets |
| Health and safety | Production/ operations | Financial analysis | End-of-life/ disposal | Public/Government R&D framework |
| Local infrastructure development | Resources/ materials required | Cost mitigation | Consumption of resources | Codes/standards—compliance |
| | Deployment | Market adoption | | Perception/position of utilities |
| | Maintenance/ warranty | Positive impact on local economy | | Security |
| | Codes/ standards—development | | | |
| | Technology roadmap | | | |

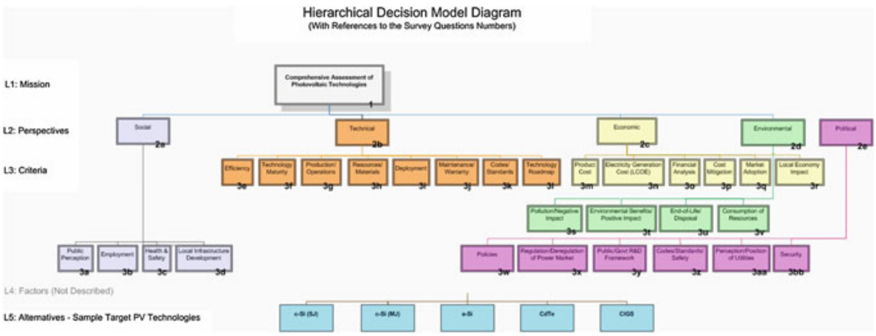


**Fig. 2** Hierarchical decision model diagram

The initial composite results for eight "technology supplier/developer world-view experts" are shown in Figs. 3, 4, 5, 6, 7, 8, 9. The initial results for this group indicated that all the multiple perspectives were important from an overall assessment point of view. The importance of the perspectives to the mission are relatively balanced ranging from relative values of 0.19–0.22. [The total is 1.00 for all five perspectives].

Evaluating and ranking the criteria for each perspective showed a certain level of variation, however, again, no one or group of criteria was dominant or stood out.

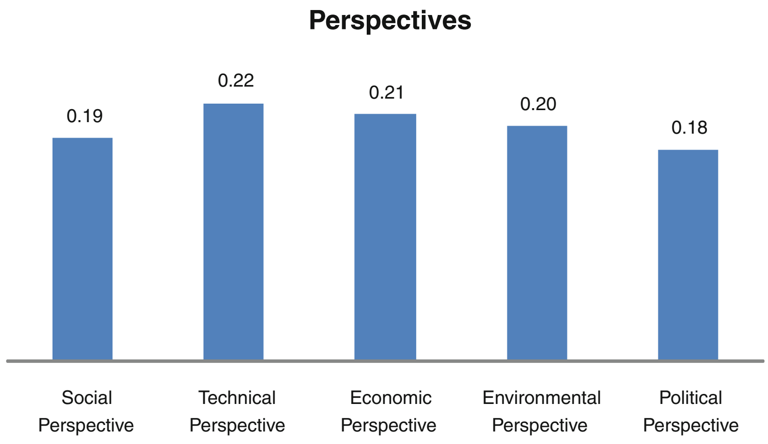


**Fig. 3** STEEP perspectives

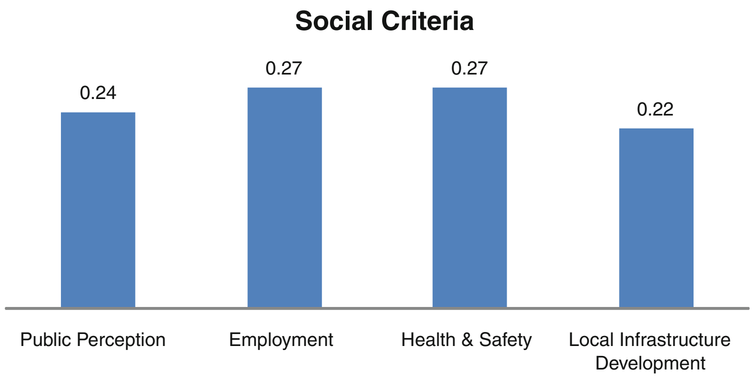


**Fig. 4** Social perspective

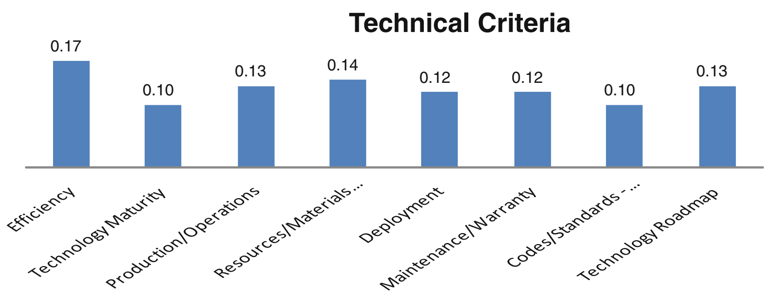


**Fig. 5** Technical perspective

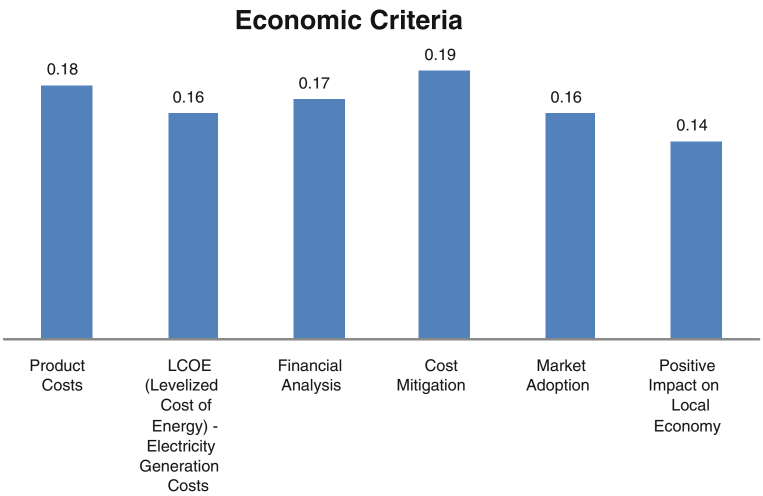


**Fig. 6** Economic perspective

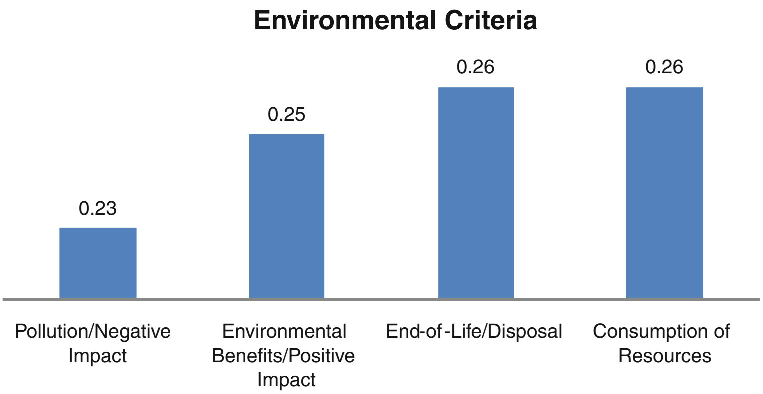


**Fig. 7** Environmental perspective

The following table (Table 2) lists the highest and lowest criterion/criteria for each perspective.

This HDM is very useful for ranking the importance of perspectives and criteria for PV technology assessment. However, it has some limitations, such as:

- It should be noted that this approach although useful to gain insight into ranking of perspectives and criteria is based on the worldview of the experts and hence reflects their worldview biases. So its scope will be useful for that particular worldview. For example, the initial results reflect the worldview of a group of technology developers.

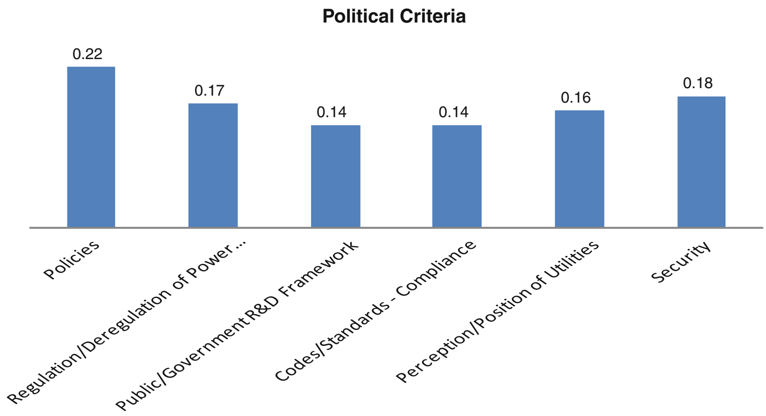


**Fig. 8** Political perspective

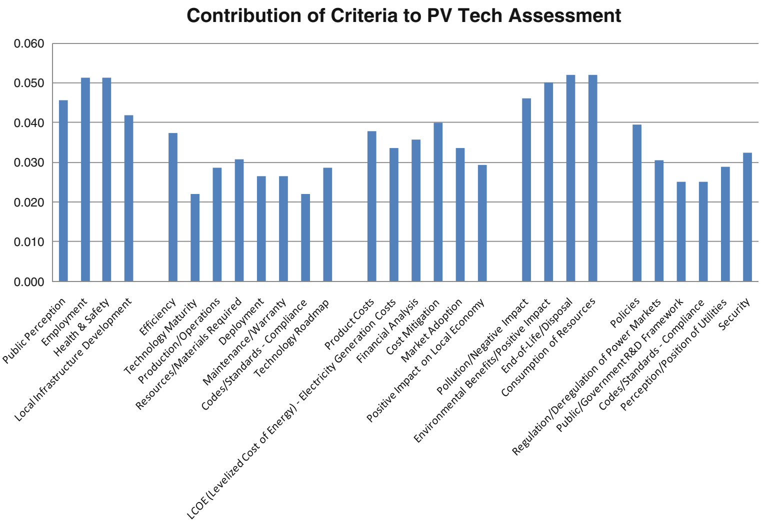


**Fig. 9** Contribution of STEEP perspectives and related criteria to PV technology assessment

- The above judgment quantification survey is one approach. Another approach may be as follows. Experts would only address the pair-wise comparison of criteria related to the perspective that is their domain of expertise. For example, technologists would only compare the criteria under the Technical Perspective, social scientists would only compare the criteria under the Social Perspective, environmental scientists would only compare the criteria under the Environmental Perspective, etc. Separately, the top five STEEP perspectives may be ranked by high level decision makers. Then all the sets of results can be combined for the final HDM analysis.

**Table 2** Highest and lowest criteria in relative importance to each perspective

| Perspective | Highest criteria | Lowest criteria |
|---|---|---|
| Social | Employment, health and Safety | Local infrastructure development |
| Technical | Efficiency | Technology maturity, codes/standards development |
| Economic | Cost mitigation | Positive impact on local economy |
| Environmental | End-of-life/disposal, consumption of resources | Pollution/negative impact |
| Political | Policies | Public/Government R&D framework, codes/ standards compliance |

- Other approaches for PV technology assessment may be simpler such as using only those top perspectives or criteria that are considered important by the industry or targeted worldview.

## 7 Conclusion

Initial results indicate interesting outcomes and provide insights into the actual explicit judgments of experts. (Refer to the section above). The initial results also helped in the clarification (or correction) of assumptions such as the Technical Perspective should be most important for those with a technology supplier or developer worldview. The initial results indicated that this may not be case (and in fact indicated that all five perspectives are relatively important) although more surveys are needed to validate or modify the findings.

The HDM model is a good method to obtain explicit judgments to better understand what is truly important for decision makers and experts. This model has the capability to be flexible and scalable with respect to multiple perspectives, multiple actors (decision makers, stakeholders, practitioners, end users, etc.), multiple criteria, and ability to provide guidance to practitioners and operational management. Hence it can provide assessment and direction. The HDM model helped in assessing both individual and group rankings of the perspectives and criteria for better analysis and indications for improvements of the survey.

## 8 Future Research

Although initial results indicated that all five STEEP perspectives were important more research is needed to test out the some of the scenarios and cases mentioned in the Initial Results and Analysis section above. Gaining insight into what is required for next steps would be more difficult without the use of HDM. Through further surveys and analyses we will be able to arrive at a robust evaluation of the criteria and perspectives. Another step would be to determine desirability functions for each sub-criteria or factor. The PV technology value (or score) can then be characterized by the composite of perspective, criteria, and factor values. This PV technology value could then be compared to the ideal value and also to its peer technologies. It is the intention of the author to pursue these future avenues of research to develop the model, analyses, and results further taking into account the initial findings from this study.

## Appendix A: Multiple Criteria and Factors for STEEP Perspectives

### *Technical Perspective*

**Efficiency**
- Module energy efficiency
- Cell energy efficiency
- Energy efficiency
- Inherent system efficiency
- Thermal efficiency
- Heating value
- PV system yield
- Reference yield
- Performance ratio
- Energy density

**Technology maturity**
- Density/maturity of patents and publications
- Identify positive trends
- Ability to bridge technology gaps
- Flexibility/scalability
- Modularity
- Obsolescence resistant

**Deployment**
- Large-scale/power plant installation
- Field testing/evaluation/performance
- Service availability (uptime of PV system)
- Reliability
- Power purchase agreements (PPAs)
- Optimized to utility scale
- Impact on meeting important energy targets
- Suitable for BIPV (Bldg integrated PV)
- Storage
- Transmission
- Distribution

**Production/operations**
- Production capacity
- No. of process steps (production processes complexity)
- Leverage mature production processes (e.g. from chip mfg)
- Chemicals/gases waste
- Wafer thickness
- Line breakage
- Production maturity

**Maintenance/warranty**
- Low maintenance
- Long lifetime (20 + years)
- Annual degradation warranty
- Management of environmental factors (dust, debris, etc.)

**Codes/standards—compliance**
- US code
- National/international standards
- Building/environmental safety standards

**Technology roadmap (2010–2030)**
- PV technology (cell/module)
- PV technology patents/publications maturity and trends
- Inverter and BOS (balance-of-system)

(continued)

| |
|---|
| **Resources/materials required**<br>• Avoid use of rare metals (e.g. indium)<br>• Avoid hazardous materials (e.g. cadmium)<br>• Resource availability/access<br>• Chemicals, gases, etc. |

## *Social Perspective*

| | |
|---|---|
| **Public perception**<br>• Aesthetics<br>• Visual Impact<br>• Heterogeneous interests, values, and worldview<br>• Engagement in public policy<br>• Conflict with planned landscape<br>• Synergistic with quality of life improvement policies<br>• Impact of lifestyle<br>• Easy/convenient to use<br>• Legacy for future generations<br>• Social benefits<br>• Social acceptance<br>• Impact on property values<br>• Impact on tourism<br>**Employment**<br>• Job creation<br>• Addition to employment diversity<br>• Availability of workforce<br>• Poverty alleviation<br>• Increase in production employment<br>• Increase in total employment | **Health and safety**<br>• Public safety<br>• Work safety<br>• Hazardous health effects (accidental, long-term)<br>• Investment in health of society (indirect)<br>**Local infrastructure development**<br>• Development/improvement of infrastructure<br>• Support of related industry<br>• Contribution to regional/local improvement<br>• Regional/local empowerment |

## *Economic Perspective*

| | |
|---|---|
| **Product costs**<br>• Capital (amortized)<br>• Startup (amortized)<br>• Materials<br>• Direct production<br>• Sales and marketing<br>• R&D/engineering<br>• Administrative<br>• Facilities<br>• Warranty/maintenance | **Cost mitigation**<br>• Independent of Economies of Scale<br>• Energy Supply Chain Advantage (e.g. against fuels)<br>• Reduction of Administrative Costs (e.g. against imports)<br>• Reduction in Subsidies (of fuels)<br>• Reduction in Military Costs (for energy)<br>• Better Use of Hard Currency (for Developing Countries) |

(continued)

- Inverter and BOS (balance-of-system)
- Installation
- Disposal/recycle (end-of-life)

**Levelized cost of energy—electricity generation costs**
- Excluding plant end-of-life shutdown/disposal
- Including plant end-of-life shutdown/disposal

**Financial analysis**
- Cost/benefit
- ROI (return on investment)
- EPBT (energy pay back time–energy viability)
- LCOE*
- Savings to power utilities
- Portfolio costs to utilities
- Costs trends/roadmap: 2010–2030
- Risk mitigation

**Market adoption**
- Market maturity
- Product/technology maturity
- Supply chain maturity
- US Code compliance
- Economic multiplier effect (through use of product)
- Customer willingness to pay

**Positive impact on local economy**
- Higher wage jobs
- Creation/expansion of economic clusters
- Job creation

Creating insourcing trend (versus outsourcing)

## *Environmental Perspective*

**Pollution/negative impact**
- GHG (Green house gases—affecting climate change)
- Particles (smoke, dust, etc.)
- Vapor
- Visual/glare
- Water
- Noise
- Solid waste
- Water resources
- Stratospheric ozone
- Soil
- Natural habitat
- Water temperature change
- Wind pattern change
- Forest and ecosystem
- Ecological footprint (crops, woods, etc.)
- During production phase
- During deployment phase
- Accidental release of chemicals

**Environmental benefits/positive impact**
- Better land utilization
- Climate change mitigation
- Environment sustainability
- Low land requirement
- Energy conservation improvement
- Better consumption of natural resources
- Reduced fossil fuel imports/dependence
- Better use of rooftops

**End-of-life/disposal**
- Biodegradability
- Easy recyclability
- Leverage mature production processes (e.g. from chip mfg)
- Chemicals/gases waste

**Consumption of resources**
- Land
- Water
- Materials

## *Political Perspective*

| Pollution/negative impact | Environmental benefits/positive impact |
|---|---|
| • GHG (Green house gases—affecting climate change) | • Better land utilization |
| • Particles (smoke, dust, etc.) | • Climate change mitigation |
| • Vapor | • Environment sustainability |
| • Visual/glare | • Low land requirement |
| • Water | • Energy conservation improvement |
| • Noise | • Better consumption of natural resources |
| • Solid waste | • Reduced fossil fuel imports/dependence |
| • Water resources | • Better use of rooftops |
| • Stratospheric ozone | **End-of-life/disposal** |
| • Soil | • Biodegradability |
| • Natural habitat | • Easy recyclability |
| • Water temperature change | • Leverage mature production processes (e.g. from chip mfg) |
| • Wind pattern change | • Chemicals/gases Waste |
| • Forest and ecosystem | **Consumption of resources** |
| • Ecological footprint (crops, woods, etc.) | • Land |
| • During production phase | • Water |
| • During deployment phase | • Materials |
| • Accidental release of chemicals | |

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# Application of Fuzzy Cognitive Map for the Development of Scenarios: A Case Study of Wind Energy Deployment

**Muhammad Amer, Tugrul Daim and Antonie Jetter**

**Abstract** In the present era characterized by uncertainty, innovation and change, scenario planning is an increasingly popular way to look at future environments because of its usefulness in times of uncertainty and complexity. Scenario planning outlines the possible futures, stimulates strategic thinking about the future and helps to overcome thinking limitations by presenting multiple futures. Developing Fuzzy Cognitive Map (FCM)-based scenarios is a very new approach. FCM is based on causal cognitive map which is an accepted intuitive method. This approach combines the benefits of both qualitative and quantitative analysis. In this study FCM-based scenarios are developed for the deployment of wind energy in a developing country to illustrate the usefulness of this approach. This study also describes the utilization of various tools proposed in the scenario planning literature to select and validate FCM-based raw scenarios. Moreover, a comparison of FCM-based scenario development approach with other prominent quantitative scenario development techniques is also presented in this chapter.

## 1 Introduction

During last 60 years scenario planning has been used in an increasing number of fields and domains [1]. Exploring the uncertainty in the business environment is the key element of scenario planning studies [2]. Especially in the present era characterized by uncertainty, innovation and change, increasing emphasis is being

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placed on the use of scenario planning techniques because of its usefulness in times of uncertainty and complexity [3]. Scenario planning stimulates strategic thinking and helps to overcome thinking limitations by creating multiple futures. Scenarios are outline of some aspects of future and generally scenario refers to an outline of the plot of a dramatic work, script of a motion picture or a television program [4]. There is no single approach to scenario planning and there are several methodologies presented in the literature for creating scenarios [4–7].

In this chapter Fuzzy Cognitive Maps (FCM)-based scenarios are developed through an expert panel. Building FCM-based scenarios is a very new approach and it is recently proposed in the literature [8, 9]. A set of FCM-based scenarios are developed for wind energy sector of a developing country in order to illustrate the usefulness of this approach.

## 2 Scenario Planning

Scenario planning has been defined in several ways. Herman Kahn (considered one of the founders of scenario planning) defines it 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" [10]. Godet describes 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 [11]. Schoemaker defines scenario planning as "a disciplined methodology for imagining possible futures in which organizational decisions may be played out" [12]. Scenario planning techniques are frequently used by managers to articulate their mental models about the future in order to make better decisions [13]. In technology planning, forecasting, strategic analysis, and foresight studies, scenarios are used to incorporate and emphasize those aspects of the world that are important to the forecast.

Systematic use of scenarios for clarifying thinking about the future started after the World War II. The US Department of Defense used it as a method for military planning in 1950s at RAND Corporation [4, 6, 14–16]. Scenario methodology was extensively used for social forecasting, public policy analysis and decision-making in 1960s. 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 [3, 17]. Therefore, it is important that while developing and analyzing scenarios, the participants/scenario creaters should be encouraged to consider options beyond the traditional operational and conceptual comfort zone of the organization [18–20]. This encouragement will help to explore new possibilities and unique insights.

Consideration of multiple possible future alternatives helps to conduct future planning in a holistic manner [21] and significantly enhance the ability to deal with uncertainty and the usefulness of overall decision making process [5, 15]. Moreover, scenario planning presents all complex elements together into a coherent, systematic, comprehensive and plausible manner [4]. Scenarios are also very useful for highlighting implications of possible future system discontinues, identifying nature and timings of these implications, and projecting consequences of a particular choice or policy decision [18].

A scenario provides the description of future situation and the development or portrayal of the path that leads us out of today and into the future [22]. A recent review of scenario planning literature reveals that main benefits of using scenarios are improvement of decision making and identification of new issues and problems which may arise in the future [5].

Research indicates that there is correlation between adoption of scenario planning techniques and uncertainty, unpredictability and instability of the overall business environment [23]. Increasing uncertainty has increased the importance of identifying 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 generally they provide greater usefulness if developed for long term [13]. Usage of scenario planning for long range planning and strategic foresight facilitates to adapt quickly to major changes [5]. Future uncertainty increases as we move away from the present and look further into the future.

Scenario planning has been extensively used at corporate level and in many cases it has been applied successful at national level [6, 24, 25]. At corporate level Shell is considered the most admired and best known user of scenarios and usage of scenarios has helped the company to cope with the oil shock and other uncertain events in 1970s [4, 6, 26]. Empirical research conducted by Linneman and Klein indicate that after the first oil crisis in early 1970s, number of U.S. companies using scenario planning techniques doubled [27, 28]. Research further reveal that at corporate level scenario planning approach was more popular among large size companies, scenarios were generally used for long range planning, and majority of scenario users belong to capital intensive industries like aerospace, petroleum etc. [27, 28].

Pierre Wack in his widely cited papers on scenario planning presented scenario building criteria based on three main principles including, identification of the predetermined elements in the environment, the ability to change mindset in order to re-perceive reality and developing macroscopic view of the business

**Table 1** Difference between scenario and projection [22]

| | 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 |

environment [2, 29–31]. Sometimes peoples confuse scenario planning with future projections. Table 1 highlights the important differences between scenario planning and future projections.

On the basis of perspective, scenarios are classified into descriptive and normative scenarios [24]. Descriptive scenarios are extrapolative in nature and present a range of future likely alternative events. Normative scenarios are goal directed and respond to policy planning concerns in order to achieve desired targets. Scenarios are also classified on the basis of scenario topic (problem specific verses global scenarios), breadth of the scenario scope (i.e. one sector verses multi-sector scenarios), focus of action (i.e. environmental verses policy scenarios), and level of aggregation (i.e. micro verses macro scenarios) [32].

## 3 Quantitative Scenario Development Methods

There are several methodologies for developing scenarios with many common characteristics [4–7]. Bradfield et al., Keough et al. and Chermack et al. review scenario building methodologies and guidelines presented in the literature [6, 7, 33]. Due to large number of scenario development techniques and models presented in the literature some authors describe it as ‘methodological chaos’ [7, 13]. The following methods are considered most popular quantitative techniques for conducting scenario planning [7, 32, 34–37]. In this section, these methods are described and compared with Fuzzy Cognitive Map (FCM)-based scenario building approach.

- Interactive Cross Impact Simulation (INTERAX)
- Interactive Future Simulations (IFS)
- Trend Impact Analysis (TIC).

### *3.1 Interactive Cross Impact Simulation (INTERAX)*

The INTERAX (Interactive Cross-Impact Simulation) methodology was developed by the Center for Futures Research (CFR)[1] at the Graduate School of Business Administration, University of Southern California [7, 35, 36]. 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 [36, 37]. Initial database has information of 100 events and 50 trend forecasts and it is

[1] CFR existed between 1971 and 1987.

updated periodically. CFR noted that scenarios developed using INTERAX approach could help companies with major decisions for a large range of issues, including new product and market opportunities, capital investments, plant and equipment acquisition, mergers and acquisitions, and R&D planning [35].

Huss and Honton state that the INTERAX approach consists of the following eight steps [36, 37]:

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 model which independently forecast the indicators based on current and past data by using econometric and time series techniques as well as forecasts available from the literature.

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

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

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

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

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.

## *3.2 Interactive Future Simulations*

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 [7, 36–38]. The main difference between IFS and INTERAX techniques is that IFS does not use Monte Carlo simulation, and it does not require an independent forecast of the key indicators or variables [36, 37].

IFS methodology consists of the following seven steps [36, 37]:

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 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, including the writing of narratives.
Step 6 Introduce low probability but high impact events and conduct other sensitivity analyses.
Step 7 Make forecasts and study implications of scenarios, and identify what strategies should be developed to take advantage of the opportunities presented while reducing potential threats.

IFS methodology emphasizes market and customer orientation, promotes a long range perspective and provides insights into business dynamics using cause and effect relationships [7, 36, 37]. Moreover this process identifies novel and diverse ideas, encourages contingency planning and provides an early warning system of major changes in the business environment [37].

## 3.3 Trend Impact Analysis

Trend Impact Analysis is another quantitative approach for developing scenarios and it has been used since 1970s. TIA is a combination of statistical extrapolations with probabilities and provides a systematic approach to combine extrapolation based upon historical trends with judgment about the probabilities and impacts of selected future events [6, 7, 34, 37]. Thus TIA considers the effects of 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 upon historical trends. Gordon describes that the following two principal steps are necessary to conduct trend impact analysis [34]:

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

The detailed methodology of TIA proposed by the Futures Group consists of the following eight steps [36, 37]:

Step 1 Select topic and identify key scenario drivers.
Step 2 Create a scenario space by selecting a subset of multiple alternative scenarios.
Step 3 Identify important impacting trends and collect time series data.
Step 4 Prepare a naive extrapolation based upon historical data.
Step 5 Establish a list of impacting events by a Delphi study, literature review, expert panel or STEEP analysis.
Step 6 Establish probabilities of events occurring over time including years to first impact, years to maximum impact, level of maximum impact, years to steady state impact, and level of steady state impact.

Step 7 Modify extrapolation and combine the impact and event probability judgments to produce an adjusted extrapolation, plus estimates of upper and lower quartile limits.

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

According to Gordon, TIA method has been used frequently and it has been applied to determine health care futures, pharmaceutical market futures, and forecast petroleum consumption in transportation to assess effectiveness of several policies [34]. 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, and Department of Transportation. It has also been used by the State of California [34].

Both TIA and CIA methodologies have some similarities, however CIA incorporates an additional layer of complexity by considering a priori probability of occurrence of events through expert judgments which may affect future [7]. In CIA approach conditional probabilities are determined in pairs for the future events through cross impact calculations. It is therefore not a standalone probabilistic forecasting tool and does not generate naive extrapolations based only on historical data [34, 36, 37]. Therefore we can conclude that CIA is relatively better approach to generate scenarios.

## 3.4 Comparison of Quantitative Scenario Planning Approaches

Comparison of the Fuzzy Cognitive Map (FCM)-based scenario planning approach with other quantitative methods for developing scenarios is presented in Table 2. The steps identified for each technique are compared with a generic set of steps for scenario planning. Huss and Honton made a comparison of the major quantitative techniques for scenario development [36, 37]. That comparison has been modified in Table 2, and FCM-based scenario development approach is compared against other prominent quantitative scenario development techniques.

It is evident from the comparison of these quantitative scenario development techniques that FCM-based scenario approach covers most of the generic set of steps for scenario planning highlighted in Table 2. FCM takes account of the various possible developments of the various factors as well as connections between these factors. Moreover, FCM-based scenarios are based on the combination of both creative (qualitative) and more structuring (semi-quantitative) approaches and it allows the stakeholders to play a vital role. Unlike the very simple models used in extrapolations, in FCM modeling we can excite the FCM matrix and examine how the values of the variables (various concepts) will change based on the relationships between them. This approach develops alternative,

**Table 2** Comparison of the quantitative scenario development technique

| Generic steps for scenario development | Fuzzy cognitive map (FCM)-based scenarios | Trend impact analysis | INTERAX | Interactive future simulations (IFS) |
|---|---|---|---|---|
| The topic | 1. Scenario preparation | 1. Identify key scenario drivers<br>2. Create scenario space | 1. Define the issue and time period of analysis | 1. Define and structure the topic |
| Key decisions | 2a. Knowledge capture | | 2. Identify the key indicators | |
| Trend extrapolation | | 3. Collect time series data<br>4. Prepare naive extrapolation | 3. Project the key indicators | |
| Influencing factors | 2b. Knowledge capture (identify key concepts and drivers) | 5. Establish list of impacting events | 4. Identify the impacting event | 2. Identify areas of influence |
| Analysis of factors | 3a. Scenario modeling | 6. Establish probs. of events occurring over time | 5. Develop event prob. distribution | 3. Define descriptors write essays; assign initial probabilities |
| Cross-impact | 3b. Scenario modeling (develop causal map, with weighted causal links) | | 6. Estimate cross impacts<br>7. Complete cross impact analysis | 4a. Complete cross impact matrix |
| Initial scenarios | 4a. Scenario development | 7. Modify extrapolation | 8. Run the model | 4b. Run the program<br>5. Select scenarios for further study |
| Sensitivity analysis | 4b. Scenario development (using different set of inputs vectors to see behavior of FCM model) | | | 6. Introduce uncertain events; conduct sensitivity analysis |
| Detailed scenarios | 5. Scenario selection and refinement | 8. Write narratives | | 7a. Prepare forecasts |
| Implications | 6. Strategic decisions | | | 7b. Study implications |

plausible and consistent future scenarios which consist of logically suited premises. Therefore, FCM is a comprehensive technique for developing scenarios.

Scenario 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 [32]. Martino cites that despite utilization of various tools to aid the scenario development, it is still a highly subjective art and scenarios remain qualitative in nature [39]. Strictly quantitative methods are often criticized because these methods rely solely on historical data and assume that same trends will prevail in future [34]. So relying only on quantitative data may result in an inaccurate forecast and extrapolation.

For scenario development generally quantitative methods are considered useful for narrowly focused projects having short time horizon while qualitative methods are considered appropriate for projects having large scope and long time horizon. Usefulness of quantitative methods declines steadily as we look further into the future whereas usefulness of qualitative approaches increases in this case [22]. However both approaches (quantitative and qualitative) are complementary and strengthen each other when used together.

Based upon literature review some weaknesses of these quantitative methods for scenario development are summarized in Table 3 [6, 7, 34–37].

## 4 Fuzzy Cognitive Map-Based Scenarios

Causal cognitive maps are also used for developing scenarios [40]. Robert Axelrod introduced cognitive maps in the 1970s to represent social scientific knowledge as an interconnected, directed graphs consisting of nodes and edges/arrows [41, 42]. Nodes represent various concepts and arrows highlight causal relationship between

**Table 3** Weaknesses of quantitative scenarios planning techniques

| Method | Weaknesses |
|---|---|
| Trend impact analysis | The method does not evaluate possible impacts which the events may have on each other |
| | Designed primarily for the evaluation of one key decision or forecast variable which is quantitative and on which historical information exists |
| | Process is sometimes constrained due to unavailability of reliable historic time series data |
| 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 |
| | The user must use some creativity in incorporating the time dynamics |
| INTERAX | There is little indication as to which scenarios are more or less likely to occur |
| | The selection of events which occur in the first interval is based solely on a random selection using the initial user entered probabilities |

various concepts. Each concept is influenced by the interconnected concepts based on the value of corresponding causal weights. The visual nature of these maps facilitates understanding of existing dependencies and contingencies between various concepts. In this approach diverse mental models of the multiple experts are captured in form of simple causal maps and this process help experts to identify key issues of the scenario domain and guide the exploration of alternative futures [8]. The mapping process fosters system thinking and allows experts to better assess their own mental models and indicate their subjective knowledge [8].

Kosko invented Fuzzy Cognitive Maps (FCM) which are extension and enhancement of a cognitive map with the additional capability to model complex chains of causal relationships through weighted causal links [43]. The links between concepts are assigned weights to quantify the strength of their causal relationships. FCMs are mainly used to analyze and aid the decision making process by investigating causal links among relevant concepts [41]. 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 [44]. Moreover in simply applying casual cognitive map can lead to large and complex models, in which the indirect effects, feedback loops and time lags are difficult to analyze [8].

FCM analyze interrelations between phenomena that are graphically represented in causal cognitive maps or influence diagrams [21]. So it graphically models the cause and effect relationships in a decision environment. In general each concept (node) in a FCM model may reflects 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. Finite number of 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 [42]. Taber and Siegel propose estimation of expert credibility weights in order to combine multiple FCMs [45].

FCM has gained considerable research interest and this approach has been applied in numerous applications in different domains [46]. FCMs have 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, emigration issues, drug control, child labor issues, and community mobilization against the AIDS epidemic [21, 42, 47–56].

FCM-based scenario development is a very new approach and recently Jetter et al. and van Vliet et al. propose the viability of FCM as a method for scenario development by conducting scenario studies on photovoltaic solar cells and Europe's future freshwater water resources [8, 9]. FCM is a powerful modeling technique and an attractive tool to improve quality of scenario planning. Kok and van Delden identify that the weak link between qualitative and quantitative scenarios is a major obstacle towards development of integrated scenarios [57]. FCM uses fuzzy logic and it can integrate qualitative knowledge with quantitative analysis. So FCM-based scenario development approach has potential to combine qualitative story-lines and quantitative models [9]. Research indicates that integration of multiple approaches in scenario building process guarantees more robust scenarios [22, 58].

The following framework has been proposed for development of FCM-based scenarios by integrating scenario planning and FCM modeling processes [8]:

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

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

Step 3 Scenario Modeling: Streamline the causal links and assign weights and signs to all links, choose squashing functions for all 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: These raw scenarios developed after step 4 are further assessed and refined.

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

FCM-based scenario planning process is conducted with the help of an FCM expert panel. Knowledge of FCM experts is captured in a weighted causal map/FCM model to identify the crucial concepts/factors. Participation of stake-holders in this process increases their input in the model and facilitates to develop consensus among them. Experts also help to identify various combinations of input vectors that represent plausible combinations of concept states. Thus FCM-based scenarios provide the benefits of intuitive scenario methods with quantitative analysis. Utility and usefulness of FCM-based scenarios significantly depends on the quality of underlying causal map, therefore it is critical to select knowledge-able experts, and carefully examine the causal relationships, uncertainties and assumptions when developing the map.

**Benefits of FCM-based Scenario**

As highlighted in Table 3, that there are several critical weaknesses of these quantitative techniques for scenarios planning. In contrast to this FCM offers several benefits and the developed scenarios can overcome these weaknesses. Following are the major benefits of using FCMs for the development of scenarios [8, 9, 41, 57, 59]:

- This approach can bridge the gap between storylines and models by combining qualitative storylines 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 like indeterminacy of cognitive maps.

- It incorporates system concept and the mapping process fosters system thinking.
- FCM-based scenarios can combine the benefits of intuitive scenario methods with 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 relative easy to use for representing structured knowledge, and the inference can be computed by numeric matrix operation.
- It can be performed in a short time.
- It has a high level of integration because cause maps and the resulting FCMs can be easily modified or extended by adding new concepts, causal links or changing the weights assigned to 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, scenario planner calculate the alternative stable states of FCM model when it settles down.
- This approach can be used to analyze both static and dynamic scenarios evolving with time.

## 5 Development of FCM Model Through Expert Panel

To explore viability of research approach proposed in the paper, Fuzzy Cognitive Map (FCM)-based scenarios are generated using expert judgment. Members of FCM expert panel were asked to provide their causal maps by highlighting the factors that will affect deployment of wind energy on large scale in a developing country. It has been recommended to provide some background material to participants of the scenario workshop so that they can have similar background information [60]. So some introductory information was also provided to them so that they can understand the context of the research along with instructions to develop causal maps.

A workshop was conducted and during the workshop the purpose of the research, basic principles for the construction of causal maps, scenarios and FCM-based scenarios were explained to the expert panel. Experts were also asked to identify the important drivers (concepts) that could be critical to influence the course of events and lead to distinctive futures. Experts were asked to look into social, technological, economic, environmental, and political aspects while identifying the factors and issues.

For the development of the FCM the following steps recommended in literature were followed [8, 9]:

- Identify and define the important factors
  - Write down on Post-its with issues
  - Cluster these issues as a map and discuss importance

- Define the causal link between these factors
  - Identify that which factors are linked together
  - Determine that the relationships is positive or negative
  - Define relative strength of relationships by assigning causal weights (a 5-point Likert-type scale is used, with values that ranged from 1, representing a very weak causal link, to 5, representing a very strong causal link)
- Review and discuss the developed FCM
- Identification of the most important factors.

The causal map from every expert was obtained individually and combined into an integrated FCM. Multiple FCMs can be combined together to capture opinion of multiple experts together in one map for further analysis [42]. After combining the FCMs, the experts were asked again to review the integrated FCM and highlight the most important and critical factors/concepts.

The integrated FCM is shown in the Fig. 1. Every node of the integrated FCM highlights one concept and direction of each arrow indicates the direction of causal link from one concept to the other concept. These concepts are interconnected with causal links representing the cause and effect relationships among the concepts. This combined map is created after obtaining individual maps from all experts. The concepts in ovals highlighted by continuous boundary line were identified by all experts in their maps (from concept 1 to concept 14 and concept 16), whereas the remaining concepts highlighted by a dotted line were identified by two experts.

The expert credibility weights are also calculated using the method proposed by Taber and Siegel [45, 47]. Figure 1 depicts 20 concepts in which 15 concepts are identified by all experts and two experts identified five additional concepts highlighted by a dotted line. Taber and Siegel recommend calculating the Hamming distance between inferences vectors from various experts and then expert credibility weights are computed. It is found that the credibility weight of the two experts who identified additional concepts is reduced because they differ from the majority. Credibility weight of the five experts, who proposed same concepts, is 0.90, whereas the credibility weight of two experts who identified additional important concepts in their FCMs is 0.75. This method estimates a lesser expert credibility weight for those experts who differs and disagrees 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. So, it is not a suitable approach for combining multiple FCMs developed for scenario planning.

Combining multiple FCMs by taking average of the expert judgment is commonly employed technique and appropriate for combining multiple FCMs developed for scenario planning. It has been used to combine multiple FCMs developed for scenario planning [8] and this approach has been used to develop the integrated FCM shown in Fig. 1.

The central objective of the FCM is to investigate the factors that will cause deployment of wind energy on large scale in a developing country (concept C10).

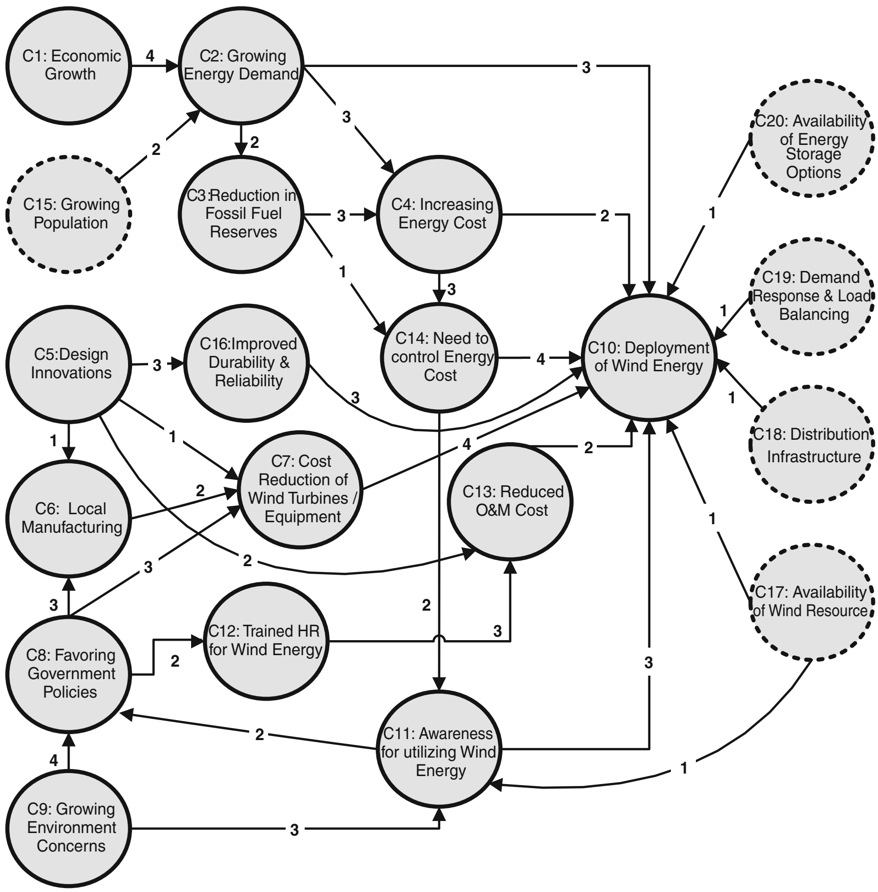


**Fig. 1** Integrated causal map/FCM for deployment of wind energy

The following twenty concepts are identified in FCM by the members of expert panel:

*C1* *Economic growth in the country*

*C2* *Growing energy demand in the country*

*C3* *Reduction in fossil fuel reserves*

*C4* *Increase in energy (electricity) cost from existing resources of energy in the country*

*C5* *Design innovations in wind turbine technology and other supporting technologies*

*C6* *Local manufacturing of wind turbines and other related equipment within the country*

*C7* *Cost reduction of wind turbines and other supporting equipment required at wind farms*

*C8* *Favoring policies adopted by the government to promote wind energy deployment in the country*
*C9* *Growing environment concerns among public and government*
*C10* *Deployment of wind energy on large scale (Objective)*
*C11* *Awareness for utilizing wind energy*
*C12* *Availability of trained HR for installation of equipment and wind farm operations*
*C13* *Low operating and maintenance (O&M) cost of wind farms due to design innovations and availability of trained workforce in the country*
*C14* Need to control energy (electricity) cost, so that electricity price remains stable despite fluctuation in oil price
*C15* *Growth in population*
*C16* *Improved durability and reliability of wind turbines and other related equipment due to design innovations*
*C17* *Availability of wind resource*
*C18* *Distribution infrastructure available to support wind energy deployment*
*C19* *Demand response and load balancing areas to cater for variability and intermittence in wind energy*
*C20* *Availability of energy storage infrastructure.*

The FCM adjacency matrix (E) of the integrated map is:

$$
E = \begin{vmatrix}
0 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 & 3 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 3 & 3 & 0 & 0 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{vmatrix}
$$

## 5.1 Identification of Important Factors (Wilson Matrix)

In scenario planning Wilson matrix is used to evaluate and prioritize the influence, impact and uncertainty of each scenario driver (concept). Wilson matrix ranks all factors against two dimensions: potential impact and probability that the driver will develop into a significant issue. So it determines degree of uncertainty and their potential impact on the future of all scenario elements [22]. Use of this matrix helps to identify critical scenario drivers which can be subsequently used to develop the raw scenarios.

In order to identify the most important scenario elements, experts are again asked to evaluate each factor (scenario driver) on the basis of their potential impact on the objective and uncertainty in a two round Delphi survey. Questionnaire was sent to fourteen experts to obtain their expert judgment. Two rounds were conducted to obtain input from the experts and after the first round feedback of the group response were also given to the experts and they were asked the same questions again. After obtaining input from the experts, Wilson matrix is developed to ranks all factors against these two dimensions: potential impact and probability that the factor will be developed into a significant issue. Wilson recommended that the categories "high", "medium" and "low" are sufficient to evaluate both dimensions [22].

Various priorities are assigned to each scenario driver (factor) based on their potential impact and probability that the factor will develop into a significant issue. The factors having high priority are highlighted in the light blue color boxes in the upper right side of the matrix. Factors having medium priority are shown in the white boxes and factors having low priority are highlighted in green color boxes in the lower left side of the matrix. Wilson matrix is shown in the Fig. 2.

Following is the priority wise ranking of various scenario drivers:

- High Priority: C1, C2, C4, C5, C8
- Medium Priority: C3, C7, C9, C11, C12, C13, C16, C17, C18, C19
- Low Priority: C6, C14, C15, C20.

Scenario drivers having high priority are important and will be subsequently used to develop the raw scenarios. It has been suggested in the scenario planning literature that scenarios with fewer but carefully examined and elaborated factors are likely to give better results [22] and many researchers recommend to consider around six key variables for scenario development [15].

These important scenario drivers, having high priority are used to form various input vectors which are subsequently used for generating FCM-based raw scenarios. However in FCM modeling all other factors in the FCM are also considered when generating raw scenarios 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 [8]. Subsequently 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

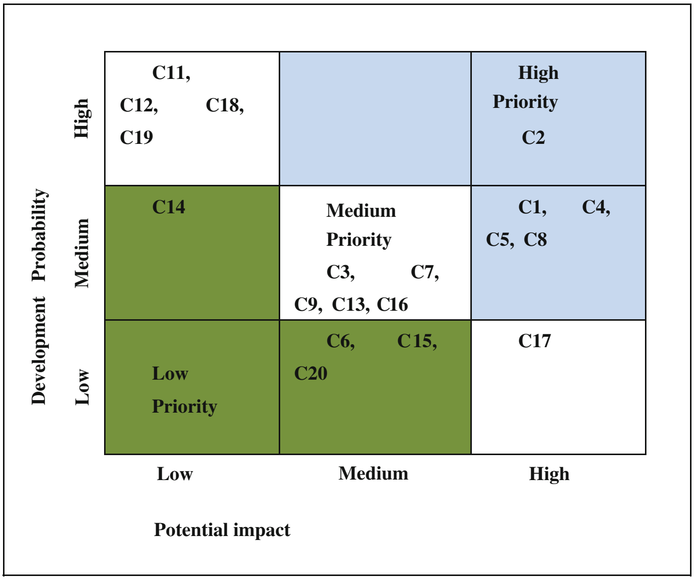


**Fig. 2** Use of Wilson matrix to prioritize scenario drivers

attains a stable state [8]. Thus we can state that despite using input vectors consisting of some the most critical scenario drivers, all factors and their causal links in the casual map are considered in the development of FCM-based scenarios.

## *5.2 Checking Consistency of the Experts*

For most of the factors consensus was achieved in the first or second Delphi round and experts confirmed their previous responses. However in a few cases there was some difference of opinion among the experts. 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 [61, 62]. Stability refers to the consistency of responses between successive rounds of a Delphi study and it is statistically verified through Chi square test using the following equation [61]:

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

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 dependent.

The responses from expert panel members for round 1 and round 2 regarding the potential impact of design innovations in wind turbines and other supporting technologies (concept 5) on the deployment of wind energy are shown in Tables 4 and 5.

The calculated value of Chi square using observed and expected frequencies indicated in Tables 4 and 5:

$$x^2 = 14.62$$

The above test has 4 degrees of freedom; it can be calculated as below:

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

The critical value Chi square ($x^2$) at 0.01 level of significance and 4 degree of freedom is 13.277. Since the Chi square value (14.62) is greater than the critical value, so the null hypothesis is rejected ($H_0$: Individual responses of rounds *i* and $i + 1$ are independent) and stability is verified.

**Table 4** Observed individual frequencies for round 1 and 2 for concept 5

| Response interval | | First round | | | Total |
|---|---|---|---|---|---|
| | | Low | Medium | High | |
| Second round | Low | 1 | – | – | 1 |
| | Medium | 1 | 2 | – | 3 |
| | High | | 1 | 9 | 10 |
| Total | | 2 | 3 | 9 | 14 |

**Table 5** Expected individual frequencies for round 1 and 2 for concept 5

| Response Interval | | First round | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Second round | Low | 0.142857 | 0.214286 | 0.642857 |
| | Medium | 0.428571 | 0.642857 | 1.928571 |
| | High | 1.428571 | 2.142857 | 6.428571 |

**Table 6** Observed individual frequencies for round 1 and 2 for concept 6

| Response interval | | First round | | | Total |
|---|---|---|---|---|---|
| | | Low | Medium | High | |
| Second round | Low | 2 | – | – | 2 |
| | Medium | 1 | 9 | – | 10 |
| | High | – | – | 2 | 2 |
| Total | | 3 | 9 | 2 | 14 |

**Table 7** Expected individual frequencies for round 1 and 2 for concept 6

| Response interval | | First round | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Second round | Low | 0.428571 | 1.285714 | 0.285714 |
| | Medium | 2.142857 | 6.428571 | 1.428571 |
| | High | 0.428571 | 1.285714 | 0.285714 |

Similarly the responses from the members of expert panel for round 1 and round 2 regarding potential impact of local manufacturing (concept 6) on the deployment of wind energy are shown in Tables 6 and 7.

Calculated value of Chi square using observed and expected frequencies given in Tables 6 and 7 is:

$$x^2 = 22.4$$

The critical value Chi square ($x^2$) is 13.27 at 0.01 level of significance and 4 degree of freedom. So the null hypothesis is rejected and stability is verified because the Chi square value (22.4) is greater than its critical value (13.27).

## 5.3 *Selection of Input Vectors (Morphological Analysis)*

After identifying the critical scenario drivers, Morphological analysis was conducted to obtain plausible input vectors for generating FCM-based raw scenarios. Fritz Zwicky proposed morphological analysis in the 1962 [63]. Morphological analysis has been used for scenarios building [14], scenario selection and refinement activities [31] and to eliminate incompatible combinations of factors [64]. The following three steps are proposed by Pillkahn to conduct the morphological analysis [22]:

Step 1 The important scenario drivers identified in Wilson matrix are mentioned at the top of the each column.

Step 2 The conceivable development variations for each scenario driver are mentioned in every row. In FCM modeling there are two states for each concept.

| Variations | C1 Economic growth | C2 Growing energy demand | C4 Increasing energy cost | C5 Design innovations | C8 Favoring government policies | Input Vector |
|---|---|---|---|---|---|---|
| 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 | Input Vector 2 1B-2B-4B-5B-8A; Input Vector3 1B-2A-4A-5A-8B |
| 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 Vector1 1A-2A-4B-5B-8B |

**Fig. 3** Morphological analysis to identify input vectors for generating raw scenarios

Step 3 Various combinations of these development variations are combined into plausible strands to generate input vectors. These input vectors will be subsequently used to generate FCM-based scenarios (Fig. 3).

In the morphological analysis diagram three strands are highlighted with different colors (shown in green, red and purple colors in the diagram) each representing an input vector for generating raw scenarios through FCM model. Morphological analysis helps to analyze and ensure that the selected combination of various variations is plausible. Scenario developer can further assess and ensure that there is no contradiction in these combinations of development variations and these strands seems to be fit together. Morphological analysis is a useful tool and it helps to visually analyze combination of various conceivable development variations for all scenario drivers. Based on these input vectors, FCM-based raw scenarios are developed and internal consistency of these raw scenarios is analyzed through consistency analysis.

## *5.4 Developing FCM-Based Raw Scenarios*

After forming the integrated FCM model and conducting the morphological analysis, two raw scenarios are generated based on input vector 1 and input vector 2. This exercise will help us to see behavior of FCM model and after that we can assess the consistency of these scenarios. In both cases after a few iterations the FCM model stabilized and settled down. The following scenarios are created.

**Scenario 1: Economic Growth**

The first scenario is based on input vector 1, where it is considered that the country is undergoing an economic growth and demand of electricity is also increasing.

Vector A represents input vector 1, when the concept 1 and the concept 2 are activated and clamped at 1, as shown below:

$$A = |1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0|$$

Then FCM simulation is performed until the output vector is stabilized. It is performed by multiplying the input vector with the FCM adjacency matrix. Squashing function is applied after every multiplication as a threshold function to the output vector. A simple binary squashing function is used which squeeze 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 is *1 by n* [47]. The new output vector is again multiplied with the FCM adjacency matrix and this process is repeated until the multiplication results in equilibrium [8, 44, 47]. As a result, system is settled down and FCM model is stabilized then new matrix multiplications will result in the same output state vector. So implications of FCM model are analyzed by clamping variables/concepts and the vector and adjacency matrix multiplication procedure, to assess the effects of these perturbations on the state of a model [46]. Thus the FCM simulation process provides a holistic overview the complete causal map and investigates the internal dynamics of the model. The input vector A is multiplied with adjacency matrix and simple binary squashing function (that converts output value of ≤0–0 and output value of >0–1) 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, represented by vector A′ as given below:

$$A' = |1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0|$$

The second order inference (vector A″) is obtained by multiplying the first inference (vector A′) with the FCM adjacency matrix € and applying the simple binary squashing function. Similarly by repeating the same procedure again we obtained the third order inference (vector A‴) and subsequent vectors.

$$A' = |1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 1\ \ 0\ \ 0\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0|$$

$$A'' = |1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 1\ \ 0\ \ 0\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0|$$

$$A''' = |1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 1\ \ 0\ \ 0\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0|$$

The result has been stabilized and settled down after fourth multiplication. We can see that besides concept 1 and 2, now concepts 3, 4, 10, 11 and 14 are also turned on in the output vector. If result is not stabilized at this level, then we would have generated further higher order inference vectors as well.

Based on FCM model and input vector, the outcome of scenario 1 indicates that economic growth and growing demand of energy in the country, will have a positive impact on the deployment of wind energy in the country despite the absence of favorable policies from the government. Moreover, this raw scenario highlights that there will be reduction in fossil fuel reserves, increase in the cost of electricity, desire to control energy cost, and increase in awareness to generate energy from wind.

**Scenario 2: Favoring Government Policies**

The second scenario is based on input vector 2, where it is considered that the government has adopted favoring policies for wind energy deployment. Vector B represents input vector 2, when the concept 8 is activated and clamped it at 1, as shown below:

$$\mathrm{B} = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0|$$

Then FCM simulation is performed until the output vector is stabilized and again simple binary squashing function is used:

$$\mathrm{B}' = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0|$$

$$\mathrm{B}'' = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0|$$

$$\mathrm{B}''' = |0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0|$$

So the output vector again stabilized after third multiplication. This second raw scenario indicates that favoring government policies for wind energy has a positive impact on the deployment of wind energy in the country. This will also have a positive effect on establishment of local wind manufacturing industry, cost reduction of wind turbines and related equipment, reduced O and M cost, and in country availability of trained human resource to support wind energy.

In general both FCM-based raw scenarios are quite plausible and can be used for further investigation. In the next section consistency analysis is performed to assess internal consistency of these raw scenarios.

**Scenario validation**

In scenario planning literature many researchers and scenario planners have identified validation criteria for scenarios. Chermack et al. state that scenarios must be checked for validity to ensure that scenarios form adequate basis for making important decisions [6]. Ian Wilson suggests five criteria for selecting scenarios [65]:

- 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 decision,
- Challenge/Novelty: the scenarios should challenge the organization's conventional wisdom about the future,
- Differentiation: they should be structurally different and not simple variations on the same theme.

Smilarly in his widely cited publication on scenario planning van der Heijden presents the following five basic criteria for scenarios [15]:

- 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 concern
- Scenarios must produce a new and original perspective on the issues.

Durance and Godet argue that scenarios should meet five conditions including; pertinence, coherency, likelihood, importance, and transparency in order to be credible and useful [14]. They further state that transparency is an important condition and without it the intended audience will not consider the scenarios [14]. Alcamo and Henrichs also propose to evaluate the scenarios on the basis of plausibility, consistency, creativity and relevance [66].

Bradfield et al. emphasize that regardless of the scenario developmental methodology; coherence, plausibility, internal consistency and logical underpinning are the common baseline criteria by which all scenarios should be validated [7]. Burt describes that scenarios should have description of a plausible future and an internally consistent account of how a future world unfolds [58]. 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 [20]. Foster state that ensuring consistency is the cardinal rule for scenario planning [67]. Schoemaker emphasizes the importance of internally consistency and plausibility in scenario building activities [17].

Porter et al. also highlight the importance of establishing criteria to evaluate validity of scenarios and suggest the following criteria for validity of scenarios [24]:

- Internal consistency of the scenarios
- Plausibility of the scenarios
- Quality of information used in the scenarios.

The following Table 8 summarizes the scenarios validation criteria proposed by various researchers and futurists in the scenario planning literature.

Summary of the scenario validation criteria highlights that the internal consistency is the most important criterion followed by plausibility. Creativity and relevance are also quite important. Plausibility of the scenario can be ensured by using the morphological analysis and consistency analysis can be used to assess internal consistency of the scenario. Methods used to select and validate the raw scenarios are summarized in the following Table 9.

The consistency analysis is also performed for the both raw scenarios and it is a useful tool to ensure consistency of raw scenarios.

**Consistency Analysis of Raw Scenarios**

Scenario planning literature emphasizes a lot on the importance of the internal consistency of the developed scenarios [6, 7, 17]. Consistency analysis is conducted to verify the internal consistency of raw scenarios. Many software tools are also

**Table 8** Summary of scenario validation criteria

| Source | Scenario validation criteria | | | | | | |
|---|---|---|---|---|---|---|---|
| | Plausibility | Consistency/ coherence | Creativity/ novelty | Relevance/ pertinence | Importance | Transparency | Completeness/ correctness |
| Alcamo and Henrichs [66] | X | X | X | X | | | |
| Van der Heijden [15] | X | X | X | X | | | |
| Durance and Godet [14] | | X | X | X | X | X | |
| Bradfield et al. [7] | X | X | | X | | | |
| Porter et al. [24] | X | X | | | | | X |
| Intuitive logics methodology [7] | X | X | X | X | | | X |
| La prospective methodology [7] | X | X | | | | | X |
| George Burt [58] | X | X | | | | | |
| de Brabandere and Alan [20] | X | X | X | X | | X | |
| Paul Schoemaker [17] | X | X | | | | | |
| Peter Schwartz [6, 69] | X | X | | | | | X |
| Peterson et al. [70] | X | X | | | | | |
| Ian Wilson [65] | X | X | X | X | | | |
| Vanston, Frisbie, Lopreato and Boston [71] | X | X | | X | | | |

**Table 9** Methods used to select and validate the raw scenarios

| Method | Purpose |
|---|---|
| Wilson matrix | Evaluate and prioritize the scenario drivers against their potential impact and uncertainty (probability to develop into a significant issue in the future) |
| Morphological analysis | Develop raw scenarios/input vectors and access plausibility |
| Cross impact analysis | Identify the strongest scenario drivers that have the highest shaping potential |
| Consistency analysis | To verify the internal consistency of raw scenarios |

available to support the consistency analysis. It is usually performed after conducting the morphological analysis and developing raw scenarios. We developed two raw scenarios through multiplication of FCM adjacency matrix and plausible input vectors. Consistency analysis is performed to verify the compatibility of combined variations of various scenario drivers (concepts) in these raw scenarios [22].

Pillkahn suggested to assign a score on a scale of 1–5 in the consistency matrix in order to evaluate the consistency of raw scenarios [22]:

- Total inconsistency: Assign a score of 1 in the consistency matrix, if there is an impossible combination consisting of two mutually exclusive events.
- Partial inconsistency: Assign a score of 2 in the consistency matrix, if the combination is partially inconsistent with some contradictions.
- Neutral: Assign a score of 3 in the consistency matrix, when there is no cross impact on each other.
- Mutual promotion: Assign a score of 4 in the consistency matrix, when there is slight positive impact of one event over the other event.
- Mutual dependency: Assign a score of 5 in the consistency matrix, when both factors are highly linked and positively impact each other.

Experts are asked to evaluate the internal consistency of two FCM-based raw scenarios by reviewing the compatibility among various scenario drivers (concepts) in these raw scenarios and ensuring that there is no contradiction in both raw scenarios. They are also asked to assign scores in the consistency matrix based on their judgment. Separate instrument was used to obtain expert judgment for conducting consistency analysis.

The results of the consistency analysis conducted for the scenario 1 and scenario 2 are shown in the Figs. 4 and 5. It is clearly evident from the consistency matrices developed for both raw scenarios that there is no impossible combination and contradiction. The score is ranging from 3 to 5 points in the consistency matrices. Thus through consistency analysis it is verified that these scenarios are internally consistent.

| | C1 | C2 | C3 | C4 | C10 | C11 | C14 | |
|---|---|---|---|---|---|---|---|---|
| C1 | | | | | | | | |
| C2 | 4 | | | | | | | |
| C3 | 3 | 4 | | | | | | |
| C4 | 3 | 5 | 4 | | | | | |
| C10 | 3 | 4 | 4 | 4 | | | | |
| C11 | 3 | 4 | 4 | 4 | 5 | | | |
| C14 | 3 | 4 | 4 | 5 | 4 | 5 | | |
| | | | | | | | | |

**Fig. 4** Consistency matrix for raw scenario 1. *1* Totally inconsistent, *2* Partially inconsistent, *3* Neutral, *4* Slight positive impact, *5* Supporting

| | C6 | C7 | C8 | C10 | C12 | C13 | |
|---|---|---|---|---|---|---|---|
| C6 | | | | | | | |
| C7 | 4 | | | | | | |
| C8 | 4 | 4 | | | | | |
| C10 | 4 | 4 | 5 | | | | |
| C12 | 3 | 3 | 4 | 4 | | | |
| C13 | 3 | 3 | 4 | 3 | 4 | | |
| | | | | | | | |

**Fig. 5** Consistency matrix for raw scenario 2. *1* Totally inconsistent, *2* Partially inconsistent, *3* Neutral, *4* Slight positive impact, *5* Supporting

The consistency analysis process is a subjective approach based upon gut feel and supposition of the experts. It is pertinent to mention that higher degree of consistency does not guarantee for sound and coherent future picture. However, it is the most important consideration for building future scenarios.

## 6 Discussion and Conclusion

This paper illustrates the development of FCM-based scenarios for wind energy deployment in a developing country. Two scenarios (Economic Growth Scenario and Favoring Government Policies Scenario) are created using the FCM model. In the first scenario, under economic growth model (concept 1 and concept 2 are clamped at = 1) and results of FCM simulation indicates an increase of deployment of wind energy in the country which seems to be plausible. For the second scenario we assumed that the government has formulated favoring policies towards wind energy deployment (concept 8 is clamped at = 1). Experts and stakeholders are asked to identify critical scenario drivers in two round Delphi survey. They provided their opinion based on intuition, research and group opinion. After obtaining expert opinion plausible combinations of input vectors were used for the generation raw scenarios. In both cases, the FCM model settled down after a few iterations and these output vectors (inferences of FCM model) represent plausible and internally consistent raw scenarios. Various tools and techniques mentioned in the scenario planning literature (Wilson matrix, morphological analysis and consistency analysis are also used to validate plausibility and consistency of raw scenarios. These tools are used for the first time to validate FCM-based scenarios. Another major strength of FCM-based scenarios is that these output vectors reflect the pattern of the underlying causal model. Therefore, this approach generates consistent and plausible scenarios, and the quantitative analysis improves the quality of these scenarios. Results of FCM simulation for both scenarios are show in Table 10.

It is clearly evident from the Table 10 that small changes in initial vectors have resulted in different stable states which can be used as raw scenarios. The set of output vectors contain pattern of the basic causal model. However, it is pertinent to mention again that usefulness and quality of FCM-based scenarios significantly depends upon the quality of underlying causal map. So it is critical to obtain input from multiple experts and carefully create the map. Moreover through FCM a relatively good structured system description is obtained within a short time. In this case, both scenarios result in an increase of deployment of wind energy in the country despite usage of different input vectors. So we can conclude that FCM can be used to create multiple plausible scenarios which represent alternative futures.

**Research Limitations**

The outputs of this research rely on expert judgment which is subjective data obtained from the members of expert panel. Limited knowledge of the experts may limit the usefulness of the FCM-based scenarios. So it is critical to carefully select the members of expert panel and ensure that they have sufficient level of knowledge and experience.

The study is primarily conducted to illustrate usefulness of this approach. FCM-based scenarios are developed on the basis of a model consisting of twenty concepts identified by the experts. Twenty concepts are not sufficient to represent all

**Table 10** Summary FCM simulation for Scenario A and B

| Scenarios | Twenty concepts of FCM model | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 | C16 | C17 | C18 | C19 | C20 |
| Scenario A | (1[a])1 | (1[a])1 | (0)1 | (0)1 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 | (0)1 | (0)1 | (0)0 | (0)0 | (0)1 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 |
| Scenario B | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 | (0)1 | (0)1 | (1[a])1 | (0)0 | (0)1 | (0)0 | (0)1 | (0)1 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 | (0)0 |

*Note* Values of start vector are shown in parenthesis i.e. ()

[a] Indicates values clamped in the start vector

the factors that may affect deployment of wind energy on large scale in a developing country. This paper built upon the initial work by Amer et al. [68].

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# Transmission Technology Assessment and Roadmapping

## A Regional Exercise

**Tugrul Daim, Sheila Bennet and Jisun Kim**

**Abstract** Bonneville Power Administration (BPA) is a Federal agency marketing and transmitting electricity power to northwest area in the US. BPA invests on research, development and demonstration (RD&D) projects to create and deliver the best value for the customers. In order to identify and support the valuable RD&D projects, BPA develops technology roadmaps in several core technology areas. The transmission technology roadmap represents the synthesis of expert opinion and technical knowledge of 80 experts across a variety of disciplines in BPA including transmission operations, planning, facility design and maintenance. It marks the beginning of an ongoing process to support decisions about RD&D investments in the northwest area of US. It provides a strategic framework to guide transmission RD&D efforts based on targets and time-based milestones. It addresses the technological challenges as well as long-term needs. This paper presents the technological needs identified for the transmission business of BPA.

## 1 Introduction

Over the years, the Bonneville Power Administration (BPA) has been successful in responding to political, business, environmental and technological drivers of change. BPA has earned regional, national and international recognition as an

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innovative leader in technical breakthroughs and achievements that have saved electric consumers millions of dollars. Throughout its notable history, BPA has made significant contributions to the original development of, and incremental improvements to, a reliable high-voltage power system, energy efficiency, non-wire solutions and environmental technologies.

Now BPA is challenged to adapt to a new environment in which technology, regulation, generation resources, customer demands and power flows are much different from 20 years ago. Moving forward, BPA management chose to use roadmapping as an analysis tool to assist with decisions about how best to proceed in the next 20 years. During the roadmapping process, critical technologies were identified that best support the agency's innovation strategy. Roadmapping also identified the RD&D gaps that exist between the current and future critical technologies. This road map will assist BPA in making RD&D investment decisions and help to identify ways to leverage RD&D investments. This road map provides strategic direction about future decisions associated with transmission technologies.

Today's environment is stretching the aging transmission system to operate at power flow levels closer to voltage, thermal and stability limits. For example, from June through August 2005, the Northwest grid power flows exceeded the grid's operating transfer capability (OTC) at least 174 times [1]. As power flow congestion incidents increasingly exceed historical levels, the system operates closer to its limits more often, thus increasing the risk to system reliability and economic efficiency [1]. Although, BPA has invested more that $1 billion in new transmission construction in the last several years, relatively speaking, this is not enough to support an aging infrastructure that is continually being pushed closer and closer to its limit.

One major way to address these concerns is to place more effort in technology innovation and confirmation and to leverage resources through coordination with other organizations that share common RD&D goals. Thus, BPA has decided to ramp up RD&D expenditures to 0.5 % of gross revenues. The BPA Technology Innovation annual budget (excluding capital investments and fish and wildlife) is expected to be $12 million by 2011 [2].

The goal of future RD&D is to transform critical technologies into best practice applications. BPA developed a roadmap for the transmission technologies to support the RD&D efforts by providing a guideline to evaluate and select the RD&D projects which will fill the technical gaps. The roadmapping process identified the critical technologies that have the potential to improve system reliability, lower rates, advance environmental stewardship and provide regional accountability. These technologies are

- Real-time wide-area control, monitoring and measurement systems;
- Situational awareness and visualization tools for operations/dispatch;
- Software tools for system performance and online real-time dispatch/operations;
- Real-time automated load forecasting and generation tools;
- Power electronics, energy storage and modular substation equipment;

- Advanced maintenance and diagnostic technologies;
- Extreme event protection and facility hardening;
- High-current operating technologies and advanced conductors; and
- Non-wire solutions.

### *1.1 Roadmapping*

As outlined by Phaal et al [3] technology roadmapping is a flexible technique which is widely used to support strategic planning. The method enables a structured and graphical means for exploring and communicating the relationships between evolving and developing markets, products and technologies over time. Many supporting methods are used to identify the market needs, existing and emerging products and technologies, and required research and development focus areas [4].

Roadmaps have been used in the government sector for policy development to promote technology development or adoption [5].

Technology Roadmaps have been used in the energy sector as well. McDowall and Eames [6] developed roadmaps for the hydrogen economy. Lee et al. [7] applied technology roadmapping process to develop a plan for technology development for the Korea Institute of Energy research. Daim and Oliver [8] reported an energy technology roadmap implementation and provided a roadmap for energy efficiency technologies. Kajikawa et al. [9] demonstrated use of other technology intelligence techniques to develop a roadmap to plan for sustainable energy development.

## 2 Drivers and Targets Shaping the Vision of the Future Grid

### *2.1 The Drivers*

A key feature of BPA's approach to defining the technology innovation targets is to explicitly base them on, and link them to, BPA business drivers. During the Planning/Operation workshop held in December 2005 and the Facility workshop held in February 2006, BPA transmission experts brainstormed to identify the drivers that are moving the agency into the future. The drivers that were identified are clustered around topics that are key to BPA's strategic agenda—enhance system reliability, increase transmission capabilities and control of power flows, employ cost effective, environmentally sound energy supply and demand and maximize asset use.

### 2.1.1 Enhance System Reliability

The BPA and related Pacific Northwest grid infrastructure are facing an increasingly complex operating environment. There has been a steady increase in the volume of complex transactions that directly affect operations, dispatch, scheduling and outage coordination. For example, from June through August 2005, power flows exceeded the flowgate OTC on the Northwest grid at least 174 times. In each of those occasions, BPA operators successfully responded within 20–30 min to bring the system back within OTC limits, meeting the new and mandatory Western Electricity Coordinating Council reliability criteria. But, this type of occurrence has been steadily increasing, causing power flow congestion incidents to exceed historical levels. The more often the system operates outside OTC limits, the greater is the risk to system reliability and economic efficiency. This disconcerting trend of increasing network congestion is forcing dispatchers to more frequently react in real time, or "emergency mode," to bring power flows within operational standards [10].

Currently, dispatchers lack tools, processes and data to predict congestion 1–5 min ahead of time, which significantly reduces their ability to deal with multiple contingencies that could occur in real time. As the 1996 Northwest power outage and the 2003 East Coast blackout forcibly demonstrated, multiple events on a system can occur at lightning speed, leaving dispatchers with little or no time to react [10].

BPA currently employs specialized measurement equipment, a wide-area measurement system (WAMS), to monitor dynamic changes on the system such as voltage, current, frequency, and real and reactive power. The ability to successfully operate in this increasingly complex environment will depend on the ability to collect, distil and disseminate vastly larger amounts of data. The challenge has been to fully use all the information available in the measured data to support real-time situational awareness and analyzes to keep the system stable, safe and reliable. Also, currently there is a lack of analytical capabilities for real-time operational decision making based on relieving thermal, voltage and stability constraints. The complexity of the power system and its dynamic network means that matching measured data to theoretical models is necessary to predict power flows 1–5 min ahead of time. To support this, it is necessary to model a large number of statistically likely contingent conditions and operating scenarios within a time frame that must be significantly shorter than present capabilities allow.

Also, BPA anticipates a future increase of local, decentralized, small-generation interconnections that will have an impact on future load composition changes. With this future increase of wind, renewable and distributed generation, there is a need for "quick and stable" integration of these energy sources into the grid. Accomplishing this while avoiding stressing the grid is a very complex task.

### 2.1.2 Increase Transmission Capabilities and Control of Power Flows

The grid's ability to transfer power is restricted by thermal flow limits on individual transmission lines and transformers, limits on acceptable bus voltage stability requirements and the North American Electric Reliability Council reliability requirements. Also, BPA has implemented Federal Energy Regulatory Commission Order 888 and subsequent revisions. A number of merchant generators has been connected to the BPA transmission network in the past 5 years. These new regulations, open access rules and market conditions have affected how BPA manages power flows and, as a consequence, have expanded the need for some transmission facilities. At the same time, BPA is experiencing increasing parallel path issues with other interconnected transmission systems, and our ability to manage flows on critical paths is becoming inadequate.

Yet, BPA's investment in transmission facilities is limited by the agency's borrowing authority and by customer pressure to control costs and keep rates as low as possible. The public also has a negative view toward building new transmission lines, particularly in urban and suburban areas that have the greatest load growth. As a result, BPA is driven to maximize the power transfer capability of the grid within existing corridors in order to increase revenues and reduce costs.

Scheduled outages for maintenance inherently conflict with the need to maximize the power transfer capability to increase revenues. As such, needed scheduled outages are increasingly harder to obtain, and the outage durations are shrinking, being "packed" into short windows of opportunity in spring and summer. This further increases the complexity of system operation and results in an inefficient use of existing transmission capacity as well as in our inability to react in a timely manner to create automated OTCs and address real-time system outages/changes.

Also, as BPA anticipates a future increase of local, decentralized and small generation interconnections, the system's robustness will be challenged to quickly integrate intermittent resources and manage changing load compositions (increased Pacific Northwest air conditioning use, for example).

### 2.1.3 Employ Cost Effective, Environmentally Sound Energy Supply and Demand

The demand for additional transmission service is growing at the same time public resistance to building new lines is increasing. A related issue is the increased difficulty in siting new transmission lines due to environmental and land use restrictions. Yet the system is currently operated at or near capacity. In order to increase transfer capability, BPA needs to meet future transmission demand with "low risk/high return" solutions such as intermittent generation, demand response and non wire solutions.

The integration of wind's intermittent generation further challenges system reliability and scheduled capacity. Wind power production varies widely and periods of strong production do not always match up with periods of peak electricity consumption. Wind resource integration presents technical challenges with regard to regulation, load following and oscillation damping. Yet, wind power is a proven renewable electricity source and is the fastest-growing renewable power in the Pacific Northwest. Since 2005, over 900 MW of wind power have been completed or are under construction, and another 600 MW or more is expected over the next 2 years. Wind power currently supplies about 3 % of the region's electricity. Project developers have asked for integration services and facilities to add over 3,000 additional MW of wind power in the region.

Demand response is a new resource to the region, appearing for the first time in the Northwest Power and Conservation Council's 2004 power plan. The Council estimates the resource at about 1,600 MW and targeted 400 MW for development within the plan period. Demand response is a change in customer electricity demand corresponding to a change in the cost of serving that demand. It can be accomplished through pricing or incentive mechanisms. Several technologies are being used to facilitate demand response efforts including smart thermostats, load control devices and third-party aggregators. Additional efforts are under way to control load response during system disturbances. WECC observed periods of prolonged voltage depression that were linked to the dynamic behavior of residential air conditioners. With larger penetration of air conditioning load in the Pacific Northwest, this issue becomes more relevant to BPA and other Pacific Northwest utilities.

BPA has included demand response in its non wire solutions initiative because reducing peak electricity use on a radial part of the transmission system can delay or obviate the need to build additional transmission facilities, thereby saving the region costs and reducing the risk of underutilizing new facilities.

### 2.1.4 Maximize Asset Use

BPA is implementing new risk, standardization and asset management practices to systemize equipment selection, maintenance and replacement. But, as each day passes, the aging transmission infrastructure becomes older and older, causing a gradual erosion of system capabilities and health. Because of minimal investment, the aging infrastructure is being challenged with increased power flows through existing transmission corridors, as BPA is driven to maximize the power transfer capability of the grid to increase revenues and reduce costs.

As the transmission infrastructure ages, it will need more planned outages for maintenance and repair even though scheduled outages for maintenance conflict with maximum asset use. While current maintenance techniques do not allow maintenance to be performed during certain system loading conditions, live-line maintenance techniques and tools would allow BPA to respond as in-service time requirements increase. However, Oregon and Washington law and the International Brotherhood of Electrical Workers Union restrict hot-line bare-handing techniques in part of BPA's service territory.

Incrementally integrating new technology with existing equipment presents coordination challenges for communication systems and equipment life cycles. Existing equipment is operated and maintained with information technologies that lag way behind other progressive digital and electronic industries. The ability to monitor the service life or condition of equipment becomes necessary as a means of extending equipment life and optimizing performance.

Also, in the near future BPA will experience a deficit in knowledge and skills as many of the older transmission experts retire. This anticipated vacuum of expertise cannot be compensated for with unrealistic expectations of quick technology fixes in materials, equipment and processes. Maximizing the use of BPA's physical infrastructure assets can only be achieved with highly trained and skilled transmission planning, operation, design, construction and maintenance experts.

### 2.1.5 Target Needs and Technology Features

**To meet Target 1:**
Enhance future grid reliability, interoperability and extreme event protection for increasingly complex system operation, an intelligent grid architecture is needed that can communicate across planning, design and operation to provide protection and control of the transmission system by assessing power flows, risk, emergency management and economics. This must be done with system wide communication processes that include software and hardware that are interoperable, high speed, secure and reliable. The features of an intelligent architecture include

- Real-time wide-area monitoring and control with adaptive protective relaying schemes;
- Analysis capabilities to identify thermal, voltage and stability constraints and dynamic changes on the system;
- Capability to model and simulate power flow scenarios with multiple contingencies; and
- Capabilities to collect, analyze, disseminate and display large volumes of real-time data.

The future grid needs to be able to perform online real-time analysis and to identify reliability risks for dispatch/operations within 0–30 min using automated tools. Future technologies will address real-time system outages/changes by being able to quickly generate reliable system limits that accurately reflect system operating configurations and create automated operational transfer capabilities (OTCs). Automated generation of OTCs for critical paths such as the I-5 corridor, where limits are entirely thermal, would increase OTCs by hundreds of MW, at times.

Dispatch needs better tools to reliably operate the system, especially during periods of high system stress, multiple planned and/or unplanned outages and high risk conditions associated with an extreme event (for example, storms, forest fires and earthquakes). Dispatch also needs better situational awareness tools that provide wide area overviews in a visual and graphic format to allow for more robust system analyzes and to alert operations/dispatch to inconsistent information and unstable conditions. Wide area control and measurements systems with enhanced features such as strategically placed phasor measurement units, direct data exchange with all WECC utilities and improved linkage into the emergency management system will increase BPA's real-time capabilities.

Real-time interoperable monitoring and measuring hardware integrated with interoperable software able to translate and convert the data collected into meaningful information to support operating decisions is required. Software engineering is required for data-base management and advanced computational and decision-support tools along with visualization and human/machine interface technologies. Exploration and prototyping is needed for new automatic control schemes that complement and enhance the control capabilities of human operators. It is essential for the ultimate acceptance of these technologies that development efforts take place in field settings with active engagement of transmission system operators and support staff.

To enhance grid reliability as the system gets increasingly more complex, reactive power and voltage support need to be maintained along with power quality during normal conditions and during disturbances. To achieve this, cost-effective control systems and power electronics are necessary for

- Reactive power and auto dispatch of remedial action,
- Smooth integration of intermittent and distributed energy generation and
- Energy storage technologies to reduce transmission stability constraints or voltage constraints.

Adding to the complexity of the future grid is the need to increase transmission line capacity within existing corridors and to take outages. To do this, BPA needs to implement high-current technologies that can reinforce 230 kV paths to support 500 kV grid operation and outages. Other options include the innovative use of existing technologies and alternating current to direct current line conversions.

As BPA moves into the future, it must quickly optimize the transition of new technologies into the aging transmission system. The agency needs technologies that support the integration of new and existing equipment based on condition, life cycle, end of life identification and interoperability. Smart diagnostic and maintenance technologies for transmission lines, substations and rights-of-way will provide increased reliability and reduce outages.

**To meet Target 2:**

Increase transmission transfer capabilities and control of power flows, an intelligent grid architecture is needed that can communicate across planning, design and operation and perform power system modeling to provide increase transmission and control of power flow. This must be done with system wide communication processes that include software and hardware that are interoperable, high speed, secure and reliable. The features of an intelligent architecture include,

- modeling and simulation of multiple contingencies to asses power flows and economics;
- power system modeling to support real-time OTC that is based on accurate forecasts of generation and load models;
- improved and expanded base case power flow capabilities that include automation tools to move from snap shot to real time;
- accurate, quality WECC base case data;
- offline case studies with captured real-time phase measurement unit data synchronized with the supervisory control and data acquisition (SCADA) system; and
- real-time monitoring hardware with software able to translate and convert the data collected into meaningful information to support design, planning and operating decisions.

The need to increase transmission line capacity and availability within existing corridors while also providing the ability to take outages can be accomplished with technologies that are able to

- provide real-time OTC,
- to operate at high current and high temperatures,
- to upgrade lines and/or upgrade voltages,
- to make use of innovate applications of existing technologies (A list of Innovative Applications of Existing Technologies is presented in Appendix 3),
- to reinforce 230 kV paths to support 500 kV grid operation and outages and
- to convert AC lines to DC.

The need for effective interconnection between BPA and WECC utilities can be achieved with technology that provides cost effective control systems for reactive power, auto dispatch of remedial action and high voltage DC transmission.

The need for effective integration of distributed energy and intermittent resources can be accomplished by scenario planning that accommodates a variety of generation resources such as renewable and distributed energy, demand response and non-wire solutions. Also it requires technologies that are capable to reduce peak load, integrate with end-user consumer systems and smooth out intermittent resources. To do this, cost effective control systems for reactive power, demand response and intermittent and distributed energy are required.

**To meet Target 3:**
Employ efficient, cost-effective, environmentally sound energy supply and demand, an effective integration of distributed energy and intermittent resources is required. This can be accomplished by scenario and probabilistic planning using real-time automated load forecasting and generation tools that can accommodate a variety of resources such as renewable and distributed energy, demand response and non-wire solutions.

Technologies with the ability to reduce peak load, integrate with end-user consumer systems and smooth out intermittent resources are also required. To do this, energy storage combined with cost effective control systems for demand response and intermittent and distributed energy are required.

The need for enabling technologies that reduce expenses and offset construction costs while making the best use of borrowing authority can be satisfied with non-wire solutions that reduce peak loads and have the capability to integrate end-use consumer systems into the grid.

**To meet Target 4:**

Maximize asset use, there is a need to increase transmission line capacity and availability within existing corridors and to increase the ability to take outages by increasing the real-time operational transfer capacity (OTC). Future technologies will address real-time system outages/changes by being able to quickly generate reliable system limits that accurately reflect system operating configurations.

The need to increase transmission line capacity and availability within existing corridors while also providing the ability to take outages can be accomplished with technologies that operate at high current and/or high temperatures, make use of innovate applications of existing technologies and reinforce 230 kV paths to support 500 kV grid operation and outages.

There is a need for enabling technologies that reduce expenses, offset construction costs, make best use of borrowing authority and optimize the transition of new technologies into the aging transmission system. This requires technologies that are capable to reduce peak load, integrate with end-user consumer systems and smooth out intermittent resources. Technologies are needed with features that support the integration of new and existing equipment based on condition, life cycle, end of life identification and interoperability. Smart diagnostic and maintenance technologies for transmission lines, advanced substations and right-of-ways will provide increased reliability and reduce outages.

To maximize asset use the system needs reactive power and voltage support. Also, it must be able to maintain power quality during normal conditions and disturbances. To achieve this, cost effective control systems and power electronics are necessary for,

- Reactive power and auto dispatch of remedial action, and
- Smooth integration of intermittent and distributed energy generation.

Continued improvement is needed in sensors to be better able to monitor various parameters of conductors, transformers, and other components in order to fully use their capacities. To support this information measurement and management systems for collecting, analyzing, displaying and disseminating large volume of real-time data are needed. Real-time monitoring hardware with software capable to translate and convert the data collected into meaningful information to support design, planning and operating decisions is required.

In addition, live-line maintenance techniques and tools are needed as in-service time requirements increase. At some point, certain lines cannot be taken out of service for maintenance, and maintenance cannot be performed during certain

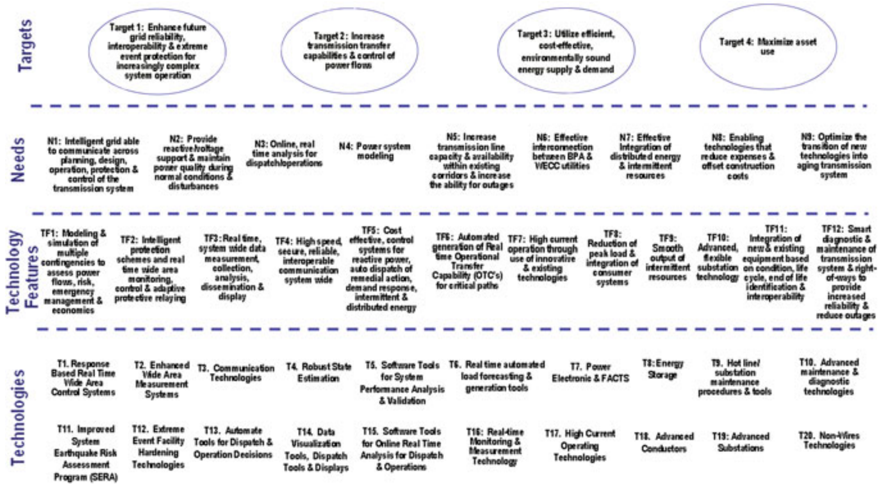



**Fig. 1** Transmission technology roadmap—targets, needs, technology features and technologies

system loading conditions. Software tools are needed to help prioritize maintenance schedules and activities.

Figure 1 shows a summary of the Transmission Technology Road map Targets, Needs, Technology Features and Technologies.

## *2.2 Technology Roadmapping*

The assessment completed the first round was followed by graphical representation of the technology needs and available technologies, when the next time the technology roadmap was updated. The following is an extract from that to demonstrate the process:

The technology roadmaps provide clarity on:

1. Key business challenges (environmental/global, market, policy and regulatory, and technology innovation) affecting the Federal Columbia River Power System (FCRPS);
2. Operational challenges created by the identified business challenges;
3. Technological needs that address the challenges;
4. Gaps in existing R&D programs designed to address identified technology needs; and
5. BPA's priorities in regard to the treatment of R&D gaps.

The Transmission Technology Roadmap specifically addresses challenges facing BPA's high voltage transmission system and its interactions with generation sources and the distribution systems of it customers. The challenges are grouped in the following major areas:

A. Transmission Planning Operational Challenges

I. Power System Modeling

(1) Development And Use Of Common System Models

II Transmission Operations

(2) Situational Awareness and Visualization Tools

III Power Grid Optimization

(3) Power Flow Controls
(4) Power System Stability Control

IV Transmission Scheduling

(5) Shorter Duration Scheduling
(6) Outage Management
(7) Congestion Management

B. New Technology Integration Challenges

V Changing Generation Resources

(8) Integration Of Variable Resources
(9) Wind Modeling

VI Changing Load Characteristics

(10) End Use (Customer/Utility) Devices.

The aim of BPA's Technology Innovation program is to provide the impetus to transform R&D into best practice applications. The roadmapping process identifies critical technologies that have the potential to improve system reliability, lower rates, advance environmental stewardship and provide regional accountability. This extract is taken from the introduction of the roadmap. We will present one of 10 areas studied in this roadmap. Section 2.3 below is an extract and provided as a demonstration of roadmap implementation.

## 2.3 *Development and Use of Common System Models Roadmap*

### 2.3.1 Business and Technology Challenges

A critical challenge for BPA's transmission modeling systems is the inconsistency of system models from power generation through transmission planning to transmission scheduling and operations. Currently, power system analyzes use multiple models and data bases that are not integrated. A common architecture is needed that can communicate across planning, design and operation to perform power system modeling that increases transmission capacity and control of power flow. It should include improved and expanded base case power flow capabilities with automation tools that move from snap shots to real time. It should include accurate, quality WECC base case data with proper labels.

This impacts several areas creating the following operational challenges:

**Identifying New System Constraints Following Dispatch Changes**

- Current models do not identify new system constraints following dispatch changes. They do not indicate which plants to turn off and which plants must stay on to provide ancillary services.
- Planning studies with perfect foresight may not match actual results when there is forecast error.
- We have difficulty in quantifying the risk of increased reliance on RAS, and redispatch.
- Models may be too optimized for one set of assumptions precluding their use for broader applications.
- We don't have good planning models for all possible operating conditions. Currently, focus is on winter peak and summer peak.

**Forecasting Congestion**

- Difficulty in forecasting congestion and congestion costs for expansion planning purposes
- Given ramp up in wind changes in system operations (Operational Transfer Capacity, Energy Imbalance Market) new storage and Demand Response resources.

**Model Consistency**

- Need more consistency of assumptions between planning and operations or more awareness of inconsistency. Planning studies do not have perfect 'Foresight'.

Another challenge due to the **insufficiency of power system models**—Current models do not simulate power flow scenarios with multiple contingencies that include intermittent and variable generation.

This results in the following operational challenges:

**Availability/Data Availability**

- Real-time interoperable monitoring and measuring hardware integrated with interoperable software is needed to translate and convert the data collected into meaningful information to support operating decisions and to get increasingly complex issues resolved faster.

**Adapting to a Changing Power System**

- Effective integration of new generation and changing load patterns requires changes to scenario planning that accommodates a variety of resources such as renewable and distributed energy, demand response and non-wire solutions. Exploration and prototyping is needed for new automatic control schemes that complement and enhance the control capabilities of human operators.

The operational and technical needs to respond to the challenges include:

**Increase Planning Scenarios**

- Need new system planning tools to develop a better planning system for more broad (encompassing) data.

**Better State Estimator Models**

- Need better state estimator models. Validate Wind Models

**Baseline Understanding of the System (Power System Performance)**

- Need for baseline performance values for an evolving system with a diversity of generation including: Oscillation baseline; Frequency response baseline; and Phase angle baseline

**Reliable source for topology/impedance model realizing elements such as load and generation models**

The required capabilities to satisfy the needs are:

**Power Plant Model Validation**

- Need baseline performance for changing generation, based on RT SE topology/impedances. Better accuracy of breakers/bus and PMUs for load and generation parameter ID.

**Scenario Analysis**

- BPA needs to run a wide range of study scenarios and process the results in a useful amount of time.

**Common System Model**

BPA needs common model data structures and parameters with tools to maintain the database and change the management process. The database will essentially be comprised of three key components; Operational breaker/node model database, Planned future system additions, dynamic database. The model will have an interface with the EMS SCADA database for real time measurements with an integrated network application environment that includes a closed loop update.

**R&D Gaps**

*Business and Technological Challenges which are not addressed by existing R&D programs*:

1. Forecasting Congestion
2. Modeling HILF (high impact low frequency), geomagnetic disturbance/geomagnetically induced currency (GMD/GIC)

3. Transformer models to evaluate the Impact of GIC for the generation of harmonics increased VAR consumption and thermal stress on transformers

*Business and Technological Challenges which are covered partially by existing R&D programs but still require further research and development*:

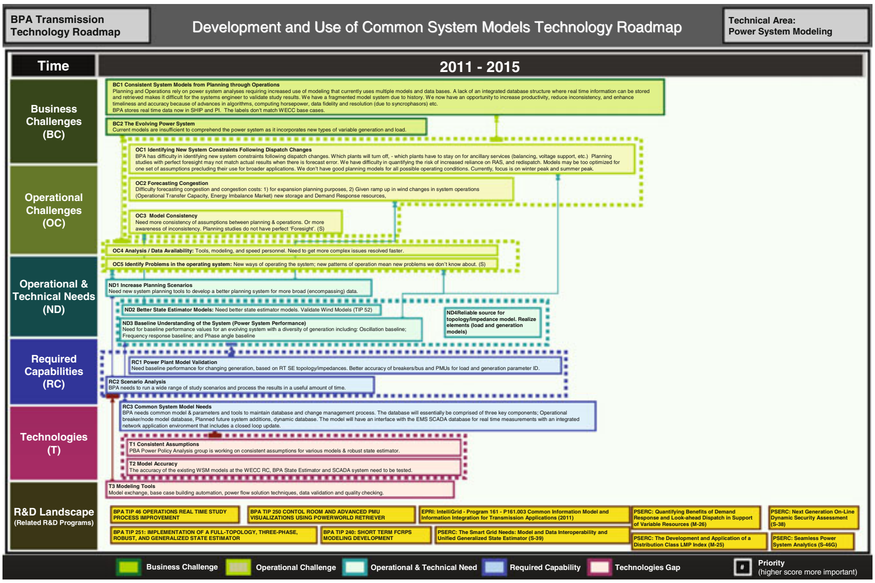
1. Model Consistency
2. Analysis/Data Availability
3. Adapting to a Changing Power System

- There are a number of Locational Marginal Pricing (LMP) methodologies currently practiced by all the Independent System Operators (ISO), Regional Transmission Organizations (RTO) and Energy Imbalance Market (EIM) operators. What is different between the current practices/methodologies for LMP and those for existing R&D projects?

*Business and Technological Challenges which are covered by commercialized technologies and products, however demonstration or confirmation studies may be required.*

1. Insufficiency of power system models: Current BPA models do not sufficiently simulate power flow scenarios with multiple contingencies that include intermittent and variable generation.
   - Almost all Energy Management Software (EMS) vendors already have state estimators that can do the above. The need is to verify if they are sufficient for BPA purposes.
2. Need to identify new system constraints following dispatch changes.

The following sections include the roadmap and descriptions of the R&D programs identified.



Related Internal and External Projects

| BPA challenge | Lead research organization | Project title and project description |
| --- | --- | --- |
| Inconsistent System Models from Planning through Operations, Models may be too optimized for one set of assumptions precluding their use for broader applications | PSERC Project Leader: Mladen Kezunovic Texas A&M University, kezunov@ece.tamu.edu, | *The Smart Grid Needs*: *Model and Data Interoperability and Unified Generalized State Estimator* (*S-39*)<br>Future Smart Grid applications such as Unified Generalized State Estimation, Intelligent Alarm Processing, and Optimized Fault Location, can benefit from the smart grid integration across data and models but the problem of data and model interoperability hinders the implementation. As an example, two difficult and interrelated problems in state estimation, ability to detect topology errors, and implementation complexity due to the two-model (node/breaker and bus/branch) architecture, will be much easier to solve if data and model interoperability are resolved. This project will identify the interoperability issues and will illustrate novel ways of their resolution in the future so that both legacy solutions, as well as future smart grid applications can utilize the same data and models but use them in a manner consistent with the application requirements and aims<br>*REVIEW*: *A number of collaborative efforts for model interoperability testing has been done at EPRI level* |

(continued)

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations, Models may be too optimized for one set of assumptions precluding their use for broader applications | EPRI | *IntelliGrid - Program 161 - P161.003 Common Information Model and Information Integration for Transmission Applications (2011)*<br>Robust and highly integrated communications and distributed computing infrastructures will be needed to create a smart grid. These infrastructures need to be interoperable across vendor equipment and throughout the enterprise. Achieving the necessary level of interoperability requires the development and industry adoption of a tightly coupled suite of standards. The Common Information Model (CIM) provides a common language for integrating applications across the enterprise and is a foundation standard for smart grids. IEC 61850, Distributed Network Protocol (DNP), and the Internet Protocol (IP) also are key standards. Significant work has been done on these standards, but a substantial amount of work is needed<br>This project develops requirements and use cases for advanced transmission operations. These requirements serve as the basis for data and device models for emerging standards as well as for contributions to standards activities within key industry organizations such as IEC, IEEE, NIST and others |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Requires changes to scenario planning that accommodates a variety of resources such as renewable and distributed energy, demand response and non-wire solutions | PSERC Project Leader: Le Xie Texas A&M, Lxie@mail.ece.tamu.edu, 979-845-7563 | *Quantifying Benefits of Demand Response and Look-ahead Dispatch in Support of Variable Resources (M-26)* The objective of this project is to conduct a first-of-its-kind empirical study on the benefits of combining look-ahead dynamic dispatch with price responsive demands for integration of variable energy resources. Based on substation level demand response data and site-specific wind generation data from ERCOT, this project will develop algorithms and a case study to quantify (1) the price elasticity of demand for typical users, and (2) the economic benefit of look-ahead dispatch with price responsive loads. To our knowledge, this is the first study to estimate demand response at the customer level for a U.S. regional system operator. Moreover, we will combine the look-ahead dispatch with the price responsive demand to quantify the system-wide benefits |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations. Current models are insufficient to simulate power flow scenarios with multiple contingencies that include intermittent and variable generation | EPRI [*Satisfies the challenge 50 %*] | **1. Existing Commercial Solutions**<br>CIM, proposed in the late 90′s<br>A formal method to define power system data using formal database models<br>EMS vendors have created converters to the CIM model from their proprietary models, but little development of CIM-native applications have occurred in the industry<br>CIM has been only partially adopted. There are ongoing users groups for CIM interoperability and development<br>Interoperability is currently limited to various vendors solving small power flow cases<br>A problem with CIM is that is very verbose, and the equivalent of planning cases requires Gbytes<br>A second problem is that is defined at the abstract level<br>**2. Ongoing Research**<br>CIM, EPRI is investigating the possibility to propose a canonical data format such as CIM. However, changes are needed to:<br>Resolve the issue of large size of power flow cases<br>CIM is an abstract model as opposed to a physical model. It is not suited for compliance because its implementation is left to the developer<br>**3. Research Needs**<br>A common, flexible data format for power systems is needed in the industry. CIM could be a good starting point, but clear model adoption roadmap, compliance mechanisms, and a vast array of applications supported must be set upfront. Organizational and cooperation mechanisms must be in place so adoption of the model does not take decades<br>*REVIEW*: *CIM supposes to be a common format and power system models can be exchanged at ease, but non of the EMS vendor CIM versions can be exchanged at this point, regardless of relentless industry efforts. This is questionable in terms of practicality*! |

(continued)

(continued)

| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Analysis and data availability, Adapting to a changing power system | PSERC Project Leader: Vijay Vittal Arizona State University, vijay.vittal@asu.edu | *Next Generation On-Line Dynamic Security Assessment (S-38)*<br>This project addresses five elemental aspects of analysis for the enhanced performance of on-line dynamic security assessment. These five elemental components includes; a) A systematic process to determine the right-sized dynamic equivalent for the phenomenon to be analyzed, b) Employing risk based analysis to select multi-element contingencies, c) Increased processing efficiency in decision-tree training, d) Using efficient trajectory sensitivity methods to evaluate stability for changing system conditions, and e) Efficient determination of the appropriate level of preventive and/or corrective control action to steer the system away from the boundary of insecurity<br>*REVIEW*: *This project is on its own merit and not related to the Common Power System Model* |
| Requires changes to scenario planning that accommodates a variety of resources such as renewable and distributed energy, demand response and non-wire solutions | PSERC Project Leader: Gerald T. Heydt Arizona State University., heydt@asu.edu | *The Development and Application of a Distribution Class LMP Index (M-25)*<br>This project focuses on the development and application of a distribution engineering analog of Locational Marginal Prices (LMPs). It is proposed to develop and apply a distribution LMP (D-LMP), which is used for energy and power flow management in networked distribution systems as well as pricing. The D-LMP will be designed to encourage the implementation of renewable resources in distribution systems in a cost effective way. The D-LMP signal may be used for control strategies such as management of distributed energy storage operation |

(continued)

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations, Models may be too optimized for one set of assumptions precluding their use for broader applications | PSERC Project Leader: James McCalley Iowa State University. jdm@iastate.edu, 515-294-4844 | *Seamless Power System Analytics (S-46G)*<br>The current approach to power system analysis has developed over the last 3–4 decades in a piecemeal approach where the various applications run separately using their own system models and formats. Although these tools have improved, the programs are still built upon core technology and software architectures from decades ago, each developed for its own unique purpose rather than an integrated approach that builds upon state-of-the-art algorithms, hardware, and modern day methods for data management across a shared environment. These limitations need to be overcome by modern analytical tools that can support modernization of the electricity industry. This project will identify design requirements to transition to a new systems analysis platform that encapsulates a comprehensive power system model with seamless analytics. Design requirements are organized as: (a) types of organizations and analysis needs of each; (b) computing applications associated with each analysis need; (c) basic functions comprising each computing application; (d) algorithm/hardware combinations associated with each function; (e) software architecture designs to facilitate seamless and computationally efficient power system analysis<br>*REVIEW*: *Too general and broad base. Need to be more specific to power system applications, software and database* |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations, Models may be too optimized for one set of assumptions precluding their use for broader applications | PSERC Project Leader: Mladen Kezunovic Texas A&M University, kezunov@ece.tamu.edu, | *The Smart Grid Needs: Model and Data Interoperability and Unified Generalized State Estimator (S-39)*<br>Future Smart Grid applications such as Unified Generalized State Estimation, Intelligent Alarm Processing, and Optimized Fault Location, can benefit from the smart grid integration across data and models but the problem of data and model interoperability hinders the implementation. As an example, two difficult and interrelated problems in state estimation, ability to detect topology errors, and implementation complexity due to the two-model (node/breaker and bus/branch) architecture, will be much easier to solve if data and model interoperability are resolved. This project will identify the interoperability issues and will illustrate novel ways of their resolution in the future so that both legacy solutions, as well as future smart grid applications can utilize the same data and models but use them in a manner consistent with the application requirements and aims. |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations, Models may be too optimized for one set of assumptions precluding their use for broader applications | EPRI | *IntelliGrid - Program 161 - P161.003 Common Information Model and Information Integration for Transmission Applications (2011*)<br>Robust and highly integrated communications and distributed computing infrastructures will be needed to create a smart grid. These infrastructures need to be interoperable across vendor equipment and throughout the enterprise. Achieving the necessary level of interoperability requires the development and industry adoption of a tightly coupled suite of standards. The Common Information Model (CIM) provides a common language for integrating applications across the enterprise and is a foundation standard for smart grids. IEC 61850, Distributed Network Protocol (DNP), and the Internet Protocol (IP) also are key standards. Significant work has been done on these standards, but a substantial amount of work is needed<br>This project develops requirements and use cases for advanced transmission operations. These requirements serve as the basis for data and device models for emerging standards as well as for contributions to standards activities within key industry organizations such as IEC, IEEE, NIST and others |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Requires changes to scenario planning that accommodates a variety of resources such as renewable and distributed energy, demand response and non-wire solutions | PSERC Project Leader: Le Xie Texas A&M, Lxie@mail.ece.tamu.edu 979-845-7563 | *Quantifying Benefits of Demand Response and Look-ahead Dispatch in Support of Variable Resources (M-26)*<br>The objective of this project is to conduct a first-of-its-kind empirical study on the benefits of combining look-ahead dynamic dispatch with price responsive demands for integration of variable energy resources. Based on substation level demand response data and site-specific wind generation data from ERCOT, this project will develop algorithms and a case study to quantify (1) the price elasticity of demand for typical users, and (2) the economic benefit of look-ahead dispatch with price responsive loads. To our knowledge, this is the first study to estimate demand response at the customer level for a U.S. regional system operator Moreover, we will combine the look-ahead dispatch with the price responsive demand to quantify the system-wide benefits |
| Inconsistent System Models from Planning through Operations. Current models are insufficient to simulate power flow scenarios with multiple contingencies that include intermittent and variable generation | Georgia Institute of Technology (Dr. Santiago Grijalva) [*Satisfies the challenge 30 %*] | **1. Ongoing Research**<br>Ongoing research on the unified data model and framework with applications to generalized state estimation<br>Further testing of performance of the unified framework for various applications including operations and planning compatibility at the N-k contingency analysis level<br>**2. Research Needs**<br>Industry-wide utilization of the unified operations and planning framework<br>Methods to test interoperability of unified models<br>Utility/ISO planning directly with node-breakers models<br>Implications of potential abandonment of bus/branch models<br>Widespread creation of WECC or Eastern Interconnection models at the node-breaker level<br>*REVIEW: Others EPRI, WECC WSM, PowerWorld, etc. have done what stated in the proposal* |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Insufficient Power System Models—Current models are insufficient to simulate power flow scenarios with multiple contingencies that include intermittent and variable generation | Project Leader: Thong Trinh Org: TS [*Satisfies the challenge 80-100 %*] | BPA EXP 16 Development of a Common Power System Model and Database<br>Increasing reliance on power system analyzes for the operation and planning of the power system has led to modeling being elevated to a critical function for both planning and operations. Models are supporting a variety of enterprise functions, and better model exchanges are needed. Today, the need for model consolidation and sharing is on everyone's mind. The necessity for: better operating tools, increased transfer capability, accurate real-time load forecasts, validation of power system dynamics, and smart grid will all carry this trend further<br>This project proposes the development of a centralized database that includes closed loop update and maintenance processes, and integrated network applications. The database will essentially be comprised of three key components: Operational breaker/node model; Planned future system additions; Dynamic database. The model will have an interface with the EMS SCADA database for real time measurements with an integrated network application environment with closed loop<br>*REVIEW*: *This is a practical approach that deals with real practical needs* |

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| BPA challenge | Lead research organization | Project title and project description |
|---|---|---|
| Inconsistent System Models from Planning through Operations. Current models are insufficient to simulate power flow scenarios with multiple contingencies that include intermittent and variable generation | Siemens | **1. Existing Commercial Solutions**<br>Siemens has created a product capable of mapping models between their EMS system and their PSSE models. Effectively the model is a case converter from the EMS to centralized database to PSSE. However, because fundamentally the planning cases loses information of the switching devices, it is not possible to "go bacK" from the planning model to the operations model. System has been deployed successfully at various control centers, ERCTO, etc<br>*REVIEW*: *First sentence is not entirely truth. MOD (Model On Demand) still not capable of completely doing as stated. This is to solely benefit Siemen PSSE product* |
| Inconsistent System Models from Planning through Operations. Current models are insufficient to simulate power flow scenarios with multiple contingencies that include intermittent and variable generation | Texas A&M (Dr. Mladen Kezunovic) [*Satisfies the challenge 5 %]* | **1. Ongoing Research**<br>Ongoing research on data model compatibility between fault detection and operational models |

# 3 Conclusions

Technology roadmaps are created to support research and development (R&D) plans that meet the strategic goals of industries and organizations with research needs. BPA's technology roadmaps are essentially a snapshot of current perspectives to inform a research agenda that will help BPA adapt to a new environment in which technology, regulation, generation resources, customer demands, and power flows are changing dramatically. The roadmapping process of BPA identifies critical technologies that have the potential to improve system reliability, lower rates, advance environmental stewardship, and provide regional accountability.

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# Forecasting the Maturity of Alternate Wind Turbine Technologies Through Patent Analysis

**Kenny Phan and Tugrul Daim**

**Abstract** The future of energy can't be solely depending on fossil fuel. Fossil fuel availability is limited and the price is volatile. The solution to the future is renewable energy. One of the widest recognized renewable energy is wind. Wind energy is considered clean, zero-carbon emitting energy source, original, diversified and show promising development in the future. This paper explored new technology in wind energy. The new technologies identified were Jet Engine Wind Turbine, Gearless Wind Turbine, Airborne Wind Turbine, Magnus Wind Turbine and LIDAR wind turbine. Those technologies are based on Horizontal Axis principle. Technology forecasting by using bibliometrics analysis, patent analysis, and growth curve were integrated in this paper. The results indicate that jet engine wind turbines are currently in early maturity stage, while gearless wind turbines, LIDAR wind turbines and Magnus wind turbines are at the end of growth curve. Airborne wind turbines are currently in the very end of growth curve and almost move to maturity stage. The findings suggest that all of those wind turbines are expected to be produced started in 2011 or 2012 and implemented widely around 2014–2016.

## 1 Introduction

Global warming and climate change are driven by the production of greenhouse gas emissions. The availability of fossil fuels is limited. The concern about global warming, climate change and the scarcity of fossil fuels have leaded us to

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renewable energy. One of the widest recognized renewable energy is Wind energy. Wind energy is getting more attention in recent years. Wind energy is considered clean, zero-carbon emitting energy source, original, diversified and show promising development in the future [1]. Wind energy is growing at 20–30 % annually making it the fastest growing new source of electricity worldwide [2]. According to Robert Thresher, Director of the U.S. Department of Energy's (DOE) national Wind Technology Center, "In the 1980s, wind cost about 40 cents per kilowatt hour. Now the cost is between 4 and 6 cents per kilowatt hour, so we've reduced the cost of wind by an order of magnitude in the past two decades [2]." This fact even strengthens the argument that wind energy will be one of the most promising renewable energy in the future. The cost will be significantly lower compared to fossil fuels that have price volatility and keep increasing from time to time. Wind energy also supported by government. Wind energy users will receive tax benefits through the federal production tax credit (PTC).

Below are the advantages of using wind energy [3]:

- Wind is naturally available and can be capture efficiently
- Zero fuel costs—abundant and inexhaustible
- Clean energy—cause no carbon dioxide emissions
- Reliable—avoid reliance on importing fuels
- Land friendly—wind turbines are usually tall which occupied only a small fraction of land on the ground. The land surrounded the tower can still be used for other activities
- Wind turbines could be an interesting feature of the landscape
- Wind turbines can benefit rural areas which are not connected to power grid
- There are variety of wind turbines available which can fit range of needs.

To be able to produce energy from wind, wind turbines are required. The current designs of wind turbines usually have 2 or more blades with diameter of rotor between 70 and 100 m. It consists of 1–3 MW. Most of the wind turbines have three blades which look like airplane's wing. This airplane's wings look alike have the ability to create lift from air over the blade. Usually, the blades are made of a composite material structure [4]. These blades are positioned on a steel towers. The heights of the towers are varying from 30 to 85 m [5]. The natural wind kinetic energy will be converted by generator of the wind turbines to electricity.

Currently, the most well recognized designs for wind turbines are Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). Horizontal Axis wind Turbines place main rotor shaft in horizontal direction. It usually requires a high wind speed and operates at high RPM. The vibration levels are quite high and can be noisy. Vertical Axis Wind Turbines place main rotor shaft in vertical direction. It usually requires low wind speed and operates at lower RPM. The vibrations levels are lower than HWAT therefore the noise levels are also lower [6]. Both wind turbines have their advantages and disadvantages.

However, up until now, research and development are still being conducted to find the most efficient design of wind turbines so that it will be able to increase the efficiency and power output of wind energy.

This paper is intended to help Wind group in Energy Trust of Oregon to find the most promising technology in wind turbines. Energy Trust of Oregon focuses mainly on small scale wind. The technologies identified in Chap. 2 are not exclusively developed to be applied to small scale wind. However, technologies are scalable. This paper believes that the technologies could be applied to utility scale or small scale wind turbines. Manufacturers can apply one of those technologies to their line of products regardless the size of the wind turbines. Therefore, the technologies in Chap. 2 are appropriate to be evaluated using technology forecasting methodology.

Forecasting methodologies used in this paper are bibliometrics, patent analysis, and growth curve. Those forecasting methodologies will be performed to identify which emerging wind turbines are showing the most promising development and close to maturity. This paper then will try to explore the key manufacturers in wind turbines that develop the emerging wind turbines.

# 2 Literature Review

## *2.1 Wind Turbine*

Wind Turbine works the opposite principle of a fan. Wind turbine is utilizing wind to make electricity. Wind turbines convert the kinetic energy of wind into mechanical power. This mechanical power can be used to move generator that will convert this mechanical power into electricity. Wind Turbines comprise of components that work as an entity, e.g. anemometer, blades, brake, controller, gearbox, generator, high speed shaft, low speed shaft, nacelle, pitch, rotor, tower, wind direction, wind vane, yaw drive and yow motor [7].

As mentioned in previous section, the most well known wind turbines designs are HAWT and VAWT. However, it is believed that the designs of wind turbines could be better in order to produce electricity more efficiently.

There are several wind turbines designs are in development. All of those designs offer different advantages. This paper has identified 5 wind turbine designs that might evolve in the future. Those wind turbines are based on Horizontal-Axis principle. This paper is not intended to focus on horizontal-axis principle. However, the development of the technology in wind turbines seems to evolve more in horizontal-axis principle rather than vertical-axis principle.

### 2.1.1 Jet Engine Wind Turbine

Jet Engine Wind Turbine is a turbine design that surrounds its blades with shroud. This shroud is based on the principles of high bypass jet engine design that is used by commercial jet engines to increase the efficiency [8]. From the front, the wind turbines will look like jet engine. When air approaches, blades will direct the air to rotor, pass it and emerges on the other side. The shroud will guides this relatively fast-moving air from outside into the area behind rotors. This mechanism will help the wind turbines to suck more air [8].

There are several advantages of jet engine wind turbine [9] which includes but not limited to: reduce the cost of generating electricity from wind power by 50 %, jet engine wind turbines can utilize wind energy more efficiently by extracting more input and producing more output, footprints would be smaller, reliability is higher than normal wind turbines because it can handle lower and higher wind better, essentially safer because it is using engineering of jet engines and can be placed nearer to populations. Last but not least, this jet engine wind turbine will reduce the size of wind turbine significantly. Reduction in size means that more wind turbines can be put together more closely than conventional wind turbines (HAWT or VAWT). Because it can be put closer together, the amount of power produced by the area of land by jet engine wind turbine also increases.

### 2.1.2 Gearless Wind Turbine

Gearless wind turbine will not depend on gearbox. In fact, the design gets rid of the gearbox completely. The rotor shaft is attached directly through generator rather than mechanical center gear. It will spin at the same speed as the blades to generate energy [10]. Some gearless wind turbines produce electricity using permanent magnet machines that allows the motion of the blade to stimulate a voltage field that lead to the creation of electrical current [11].

The advantages of using gearless wind turbines are [12]: higher reliability because it does not break easily, cost saving because maintenance frequency will be lower, high efficiency because direct gearless drive eliminates gear loss, low noise and less influence to grid [11].

### 2.1.3 Magnus Wind Turbine

Magnus wind turbine can be described as a wind turbine that consist of rotating part and non rotating root parts that looks like cylinders with additional spiral-shaped structures. It also has a part called turbulators. The rotating cylinders will create the Magnus force and the spiral-shaped structures will create the driving force. The whole process will ensures an aerodynamic principle [12].

There are several advantages of Magnus wind turbine over the conventional wind turbines [12] e.g. the rotation is low speed that decrease the noise and increase the long lasting durability, help improve environmental by reducing green house emissions, the unique design will create curiosity that lead to great environmental education, it can work with a low wind velocity, rotating cylinder will create more stability because it is automatically optimized to incarcerate various wind velocity.

### 2.1.4 Airborne Wind Turbine

Airborne wind turbine is a wind turbine that is floating and supported in the air without tower and it is controlled by computer. It floats around 2000 feet height and generated power that will be transferred to the ground through tether which later will be ready for consumption via a power grid [13].

The idea of this wind turbine lies on the height of the wind turbine itself. With higher altitude, wind speed and consistency can be maintained which will result in more power, more often. Therefore, electricity production can be more significant compare to conventional wind turbines.

There are several advantages of airborne wind turbine [14, 15], e.g. the energy production will be more consistent, the capital cost is fairly lower than conventional wind turbines, it delivers the most cost-effective renewable energy, lower noise, birds and bats friendly, less footprint, mobile and easy to install closer to power grid and ideal for off grid applications.

### 2.1.5 LIDAR Wind Turbine

LIDAR is shortened from Light Detection and Ranging. LIDAR wind turbine is the new generation of wind turbine that uses laser to analyze and predict wind speeds, directions, gusts and turbulence. The laser will help the wind turbines to anticipate the upcoming wind by position the wind turbine and adjust it toward the wind so it will be used more efficiently. By doing that, it can help to preserve the wind turbine to live longer [16].

The LIDAR is usually positioned on a wind turbine rotor. It constantly adjusts the blades so that the components are protected. The energy production will increase and the extreme loads will be decreased. The laser will scan the wind and transfer the information to fiber optic detector that will fed to on-board processor [17].

The advantages of using LIDAR wind turbines [16, 17] e.g. increase energy production by up to 10 % because the possibility of using longer blades, it can significantly reduce the CO2 emissions because of the smart Laser, greater energy capture and machine lifetime is longer.

All those wind turbine show promising application in wind energy. If they all are well developed, a lot of parties will benefit from the application. It is very difficult to choose or predict which wind turbines are in steady developing stages since all the wind turbines above are still in emerging stage. Chapter 3 will use bibliometrics and patent analysis method to analyze all of the emerging wind turbines. Growth curve will show the development curve of each of the wind turbines. The information from the analysis will help decision maker to be able to make a better assessment and decision on which wind turbines they should pursue or focus on.

## 2.2 Technology Forecasting

Technology is not static. Technology will keep developing and the existing technology might become obsolete in the future. It is very difficult for companies to decide whether they should optimize the usage of the current technology or develop and move to the new technology. Technology forecasting will help technology managers to sustain competitive advantage by forecasting and assessing the technological development [18]. Not only that, technology forecasting will also help companies in anticipating the direction and pace of changes as well as identify and evaluate market opportunities or threats, develops administrative strategies, and adjusting R&D activities with new product development [19]. Technology forecasting requires company to continuously monitor technology development which will give the company the opportunity for early identification of future application and its potential development. Technology forecasting usually focuses on particular technology fields and aims to find the most promising technology in the future [19]. Technology forecasting is different from technology speculation. Technology forecasting attempts to forecast based on available data through the use of logical and explicit methods [20]. It can be used for short term or long term exercise. Short term will range from 1 to 2 years, medium will be up to 10 years and long term will be up to 20 years. The longer the time frame, the accuracy of the forecasting will be more challenging [21].

There are two types of technology forecasting. The first one is exploratory technology forecasting which based on today's knowledge and leaning towards the future. The second one is normative technological forecasting that start from future scenarios and work backwards to the present [21].

There are several technology forecasting methods available to facilitate managers on forecasting technology. Technology forecasting methods are divided into several categories. They are expert opinion, trend analysis, statistical methods, monitoring and intelligence methods, modeling and simulation, scenario planning, economic methods, descriptive and matrices methods and creativity [18, 20]. Expert opinion will ask the opinion of experts related to the subject matter. It usually will involve interrogation followed by feedback of responses. The examples of expert opinions are Delphi method, focus group, etc. Trend Analysis will look at the trend to forecast the technology. It is related to technology life cycle and predicts when technology will reach a particular life cycle stage. The examples of trend analysis are growth curve, trend impact analysis, etc. Monitoring and intelligence method will monitor variations, environmental scan, and technology watch for the forecasting attributes, for example: bibliometrics. Statistical method will utilize available historical data for forecasting purpose. The examples of statistical method are correlation analysis, risk analysis, etc. Modeling and simulation are also used in forecasting method by using a simulation that is a simplified version of real world problems. Examples of Modeling and simulation methods are agent modeling, cross impact analysis, etc. Scenario planning will depict several scenarios based on assumptions that have been validated for forecasting method, for example: scenario simulation. Economics method will employ mathematical approach for forecasting method. Examples of economic method are decision analysis, cost-benefit analysis, etc. Descriptive and Matrices method are also popular in forecasting technology. Examples of this method are roadmapping, social impact assessment, mitigation analysis, etc. Last but not least, creativity method is also used in forecasting method. The famous example of creativity is TRIZ.

## 3 Methodology

Technology forecasting methods to forecast the wind turbines in this paper are bibliometics, patent analysis and growth curve. Bibliometrics will analyze the trend by finding the text and literature from scientific publications. Patent analysis will plot and count the number of related patents to see the industries' trends. The growth curve will plot the trend of accumulative patents for jet engine wind turbine, gearless wind turbine, airborne wind turbine, magnus wind turbine, and LIDAR wind turbine.

Bibliometrics is a methodology that measures and analyzes the enormous amount of texts and literatures of specific technology [22, 23]. Bibliometrics method will capture the information in the body of the content and identify the hidden-pattern of the literatures. According to [24], bibliometrics will help researchers in the decision making process by exploring, organizing, and analyzing the historical data. It provides an interesting data source of R&D activities. Not only that, bibliometrics also provides nicely accessible and cost-effective information [25]. There are three types of bibliometrics analysis, e.g. citation analysis, patent analysis and publication analysis [26]. Citation analysis will examine the patterns among papers to identify the interaction of papers. Patent analysis will study related patents to explore industries' interests and trends. Publication analysis will look into papers or articles that examine the subject matter and as such tell indicators of R&D Activities [26]. Bibliometrics method being used in this paper is publication analysis and patent analysis. The source of bibliometrics used in this paper is Compendex (Engineering Village Database). This paper will search the publications related to gearless wind turbine, Magnus wind turbine, jet engine wind turbine, airborne wind turbine and LIDAR wind turbine from 1969 to 2010.

One or more keywords are used to search the publications. Some wind turbines are pretty straight forward for example: jet engine wind turbine. However, some will have different names of the wind turbine for example: Gearless wind turbine will also be called direct drive generator turbine.

Below is the table that represents the keywords being used to search the publications related to the emerging wind turbines

Patent analysis will analyze the number of patents to explore the technological competitiveness and technology trend in the industries. Patent analysis is straightforward and adequate to perform the analysis because of the availability of free patent databases. By counting the number of patents registered by firms, this paper will be able to present the trends in research and business environment [27]. Also, measuring the growth of number of patents in a specific technology by using keywords can recognize the overall technology forecasting model [24]. For the patent counts, this paper gathers the information of patents from United States Patent and Trademark Office (USTPO), European Patent Organization (EPO), and World Intellectual Property Organization (WIPO). The keywords being used for each wind turbines are the same with bibliometrics keywords presented in Table 1.

This paper will assume diffusion of the wind turbine technologies as measured by number of patents and publications.

This paper utilize growth curve to map the patent activities. It will forecast the technology by fitting a growth curve to a set of data, and then extrapolating the growth curve beyond the range of the data to obtain an estimate future performance. There most frequent used growth curves for forecasting are pearl growth curves and Gompertz curve. Pearl curve also known as logistic curve, and it is well-known for its usage for population forecasting. Pearl curve is usually symmetric at the infliction point and plots a straight line. Gompertz curve depict a curve where the development is the slowest in the beginning and the end of the time period. At the infliction point, Gompertz curve is not symmetric and does not plot a straight line. Generally, pearl curve will be used for forecasting technology substitution. Meanwhile, Gompertz curve is mostly used to forecast absolute technical performance [21].

Since, we are looking on emerging of wind turbine to substitute the current wind turbine, this paper will use Pearl growth curve with the following formula [28]:

$$Y = \frac{L}{1 + \alpha e^{-bt}}$$

Where:

L the upper limit to growth of Y
T time (Y is a function of time)
e the base of natural logarithms

Change in $\alpha$ affect location only, while changes in b affect the shape only.

The upper limit of the growth curve is based on assumption of similar technology. In this chapter, all the emerging wind turbines will be plotted in refer to Horizontal Axis Wind Turbine that has matured. The pearl curve above will represent annual accumulative growth. The S curve indicated that the beginning of

**Table 1** Bibliometrics key word search

| Jet engine wind turbine | Gearless wind turbine | Airborne wind turbine | Magnus effect wind turbine | LIDAR wind turbine |
|---|---|---|---|---|
| Jet Engine wind turbine | Gearless wind turbine<br>Direct drive generator wind turbine<br>Permanent magnet synchronous generator wind turbine | Airborne wind turbine<br>Aerial wind turbine | Magnus wind turbine<br>Spiral magnus wind turbine | LIDAR wind turbine<br>Light detention wind turbine |

the time period will be slow and increase in the adoption phase and slowing down when the technology approach maturity [29]. The results of the pearl curve plotted from the number of patents will help researchers to understand the technology trends in the future [30].

# 4 Results and Analysis

## *4.1 Bibliometrics Analysis*

The searching of the keyword in bibliometrics analysis utilized Compendex (Engineering Village) database. The searching includes the publications from 1969 to 2010 using the keywords presented in Table 1. Figures 1, 2, 3, 4, 5 will give illustrations of the publications development for each wind turbine with X-axis represents the year and Y-axis represents number of publications. Figure 1 show the

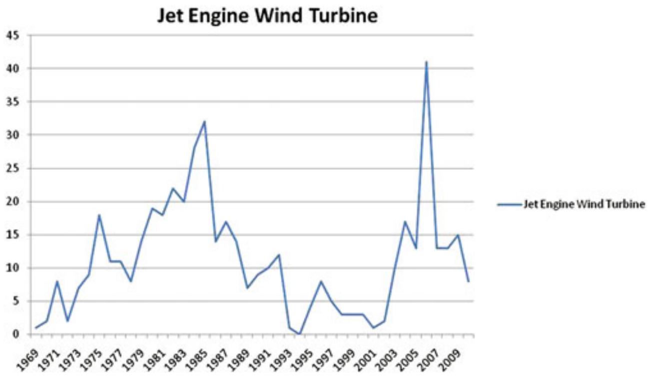


**Fig. 1** Number of publications of jet engine wind turbine by year

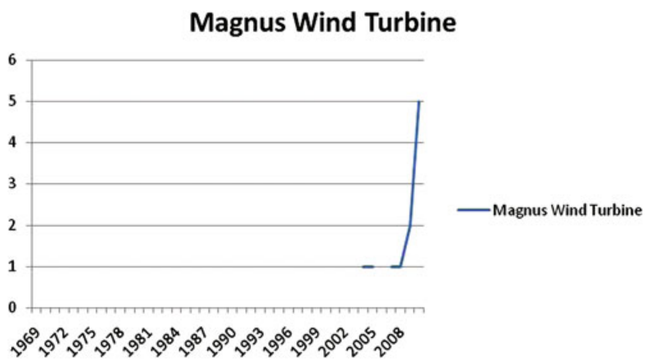


**Fig. 2** Number of publications of magnus wind turbine by year

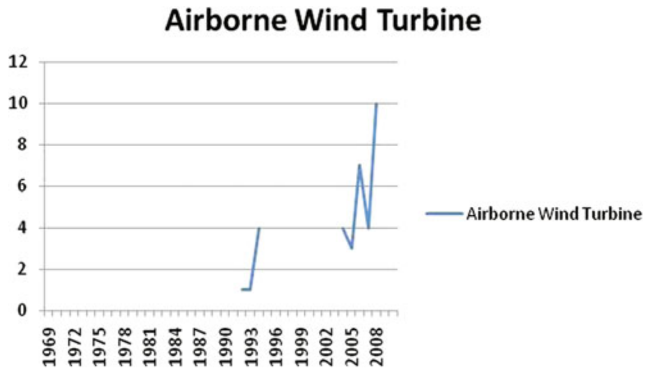


**Fig. 3** Number of publications of magnus wind turbine by year

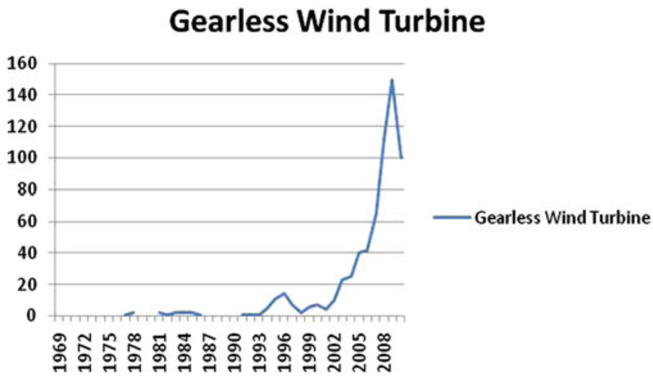


**Fig. 4** Number of publications of gearless wind turbine by year

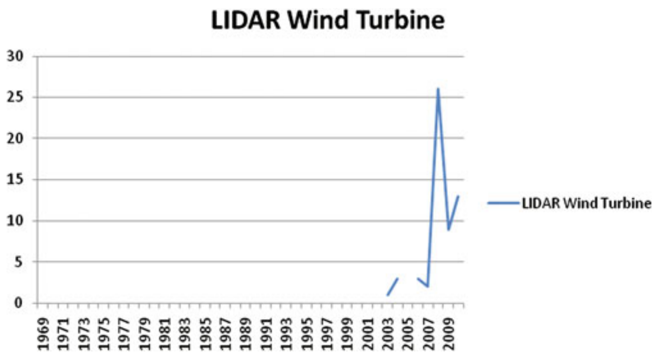


**Fig. 5** Number of publications of LIDAR wind turbine by year

growth of publications related to jet engine wind turbine. The numbers of publications decrease after 2007. The speculation is the technology is close to maturity and it will be incorporated with other technology. Magnus wind turbine shows a slow development over time. The publications related to Magnus Wind Turbine first appeared in 1981 and since then, not too many publications were published in this area. Similar thing also happened with LIDAR wind turbine and airborne wind turbine. The publications growth of these two wind turbine are not constant. Some years show no activity in the publications, therefore the graphs are not continuous. The speculation for Magnus, LIDAR and airborne wind turbine is these technologies still in development stage, therefore the publications related to these wind turbines are still developing over time. Gearless wind turbine shows that this technology is still developing especially in the past 5 years. The publications related to gearless wind turbine show significant improvement in the past 5 years.

From the publication analysis above, we can see that gearless wind turbine leads in the publications numbers especially in the past 5 years. Even though the graph of the publications does not show the continuity compare to jet engine graph, however the total number of publications of gearless wind turbine exceed publications of jet engine wind turbine. Jet engine wind turbine comes behind gearless wind turbine and show continuity of publications over time. Magnus, LIDAR and airborne wind turbine does not show the publications trends in its area since the graph of the publication growth showing a limited number of publications.

### *4.2 Patent Analysis*

A group of researchers focused on the value of patenting. Ernst et al. [31] explored the value of patent protection. Chen and Chang [32] correlated patent quality to the market value of a firm.

One major stream of researchers used patent analysis for technological planning and forecasting. Lee et al. [33] used patent analysis for technology roadmapping. Li [34] also used patent analysis for the same purpose. Choi et al. [35] integrated patent analysis into cross impact analysis to estimate the technological impact of information and communication technologies. Lee at al [36] used patent analysis to develop technology maps to identify opportunities for new technological innovations. Pilkington [37] introduced a statistically driven patent-based method to predict technology diffusion.

A group of researchers focused on evaluating the history of the technology development. Ma et al. [38] explored China's technological capability and the level of its international collaboration using patent analysis. Ma and Lee [39] repeated a similar analysis for South Korea and Taiwan. Sun et al. [40] used a similar approach to explore the patterns in environmental technology innovations. Haustein and Neuwirth [41] used patent analysis to identify the long term trends which they called as long cycles. Lee et al. [42] used patent analysis with several other methods to identify the forced diffusion patterns of technological innovations in the automotive industry. Lo Storto [43] also explored technological innovation strategies this time in Europe using patent analysis. Hung and Tang [44] used patent analysis to explore technology acquisition in the electronic industries of Japan, Korea and Taiwan. Tsuji [45] identified that Canon's patent acquisition strategy effectively promotes their research and development (R&D). Abraham and Moitra [46] used patent analysis to explore patterns in technological innovations in India. Archibugi and Planta [47] also used patent analysis to explore trends in technological innovations. Hanel [48] explored technology flows with methods including patent analysis.

A related group focused on the network of patents. Choi and Park [49] used citation networks to identify the technology development paths. Chang et al. [50] used patent citations to explore technology diffusion.

Patent analysis will count number of patents (including application and approved patents) USTPO, EPO, and WIPO.

Figures 6, 7, 8, 9, 10 illustrate the number of patents (cumulative) for each wind turbine with X-axis represents the year and Y-axis represents number of cumulative patents.

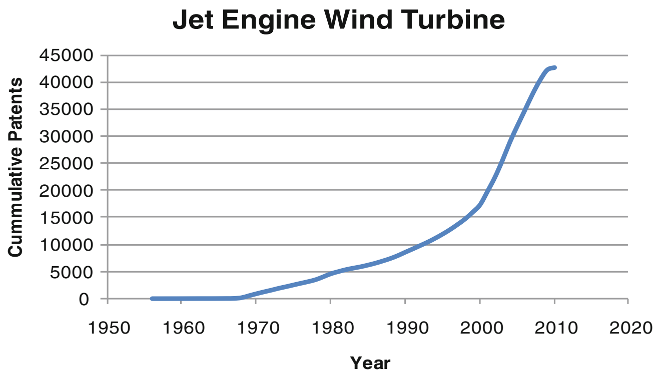


**Fig. 6** Number of cumulative patents of jet engine wind turbine by year

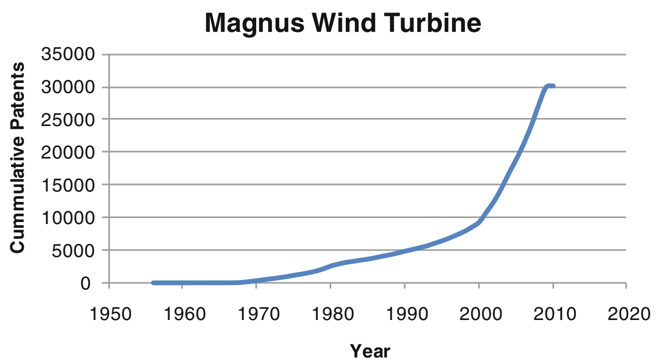


**Fig. 7** Number of cumulative patents of magnus wind turbine by year

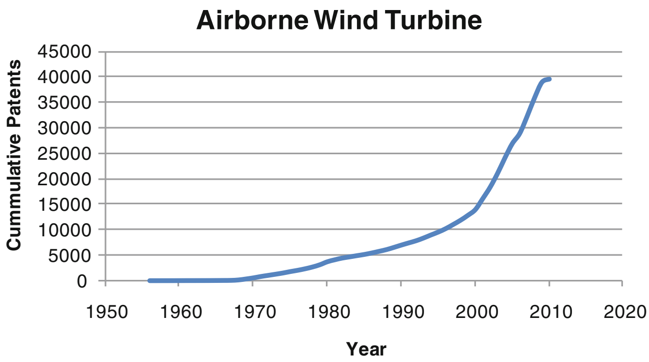


**Fig. 8** Number of cumulative patents of airborne wind turbine by year

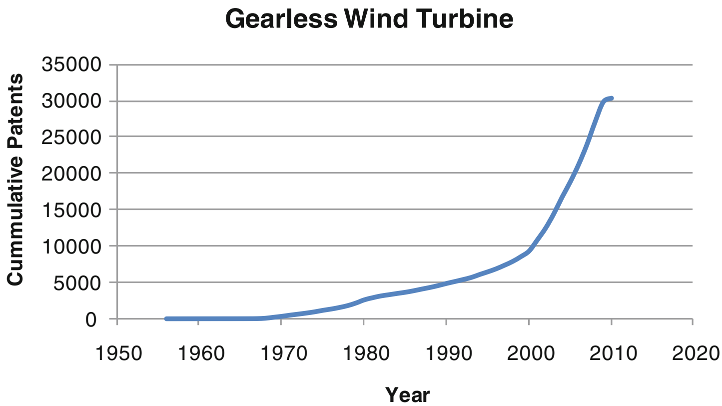


**Fig. 9** Number of cumulative patents of gearless wind turbine by year

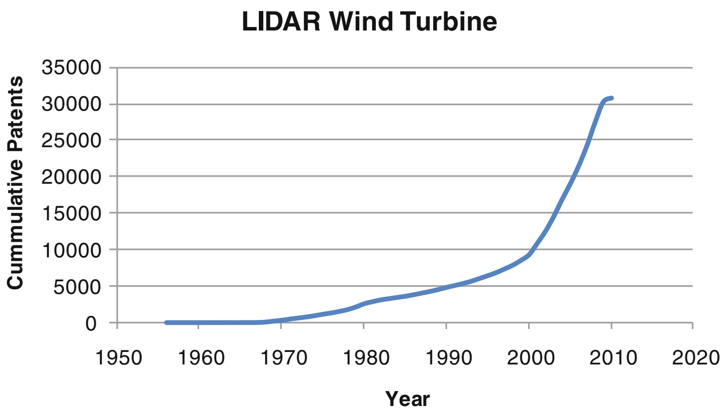


**Fig. 10** Number of cumulative patents of LIDAR wind turbine by year

From the graphs presented, we can see that jet engine wind turbine, gearless wind turbine, Magnus wind turbine, airborne wind turbine and LIDAR wind turbine have been continuously increasing over time. The growth of the number of patents for those wind turbines show similar pattern which is slow and constant in the early 1960–1980s and increased significantly after 2000s.

From the patent analysis above, jet engine wind turbine has the most cumulative patents compare to the other wind turbines. Airborne wind turbine is number two in term of number of patents. Magnus, LIDAR and gearless wind turbine fall in the same range of number of cumulative patents. However, all of those wind turbines do not dominate significantly in term of number. From patent analysis, the progress and growth of each wind turbine is illustrated better than bibliometrics analysis. The activity and indicators of the growth of each wind turbine are not documented well in publications. From bibliometrics analysis, only the growth of jet engine wind turbine is shown in a comprehensive and continuing manner. Other wind turbines are presented quite weakly. Patent analysis has more comprehensive illustration of the development of each wind turbine. The graph show the increasing and continuity growth of each turbine. The shapes of these plots are similar to that of the s-shaped growth curve [24]. From the plot above we can see that all the wind turbines can still be improved over time and have not reached saturation point. It means that all of those wind turbines will stay in the market for some time until they reach saturation point.

### *4.3 Growth Curve*

Since all the wind turbines show the similar pattern in growth from the cumulative patent counts, this paper is going to conduct growth curve of each wind turbine to find the contender that have the most promising application. In order to do that, we are going to plot the number of cumulative patents into pearl curve formula to generate S-Curve. From the historical data, the formula will find S-curve that fit the cumulative patent counts. Bootstrap analysis was also performed to find the forecast area for each of wind turbine. Bootstrap analysis will create pseudo-replicate datasets by randomly re-sampling the original data [51]. Bootstrap analysis will give us information about the confidence interval for the forecasting of the wind turbines. This paper utilizes loglet lab software to help computing the re-sampling of the original data set. The results will be shown in Figures 11, 12, 13, 14, 15 along with the S-curve for each wind turbine.

From the graph above, we can see that Jet Engine Wind Turbine is in the early maturity stage. The midpoint for jet engine wind turbine was in 2009. Jet Engine is predicted will reach the saturation point around 2032. Gearless wind turbine, LIDAR wind turbine and Magnus wind turbine are at the same stage. Those wind turbines almost reach the maturity stage with the midpoint in 2016 and reach the saturation point in 2038. It makes sense since the pattern of cumulative patents for those wind turbines are pretty similar. Airborne wind turbine is currently in the

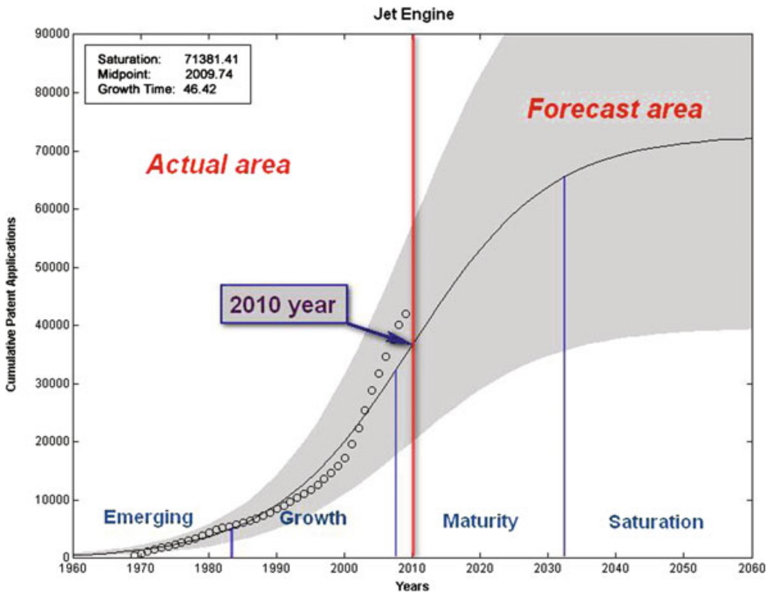


**Fig. 11** Jet engine wind turbine growth curve

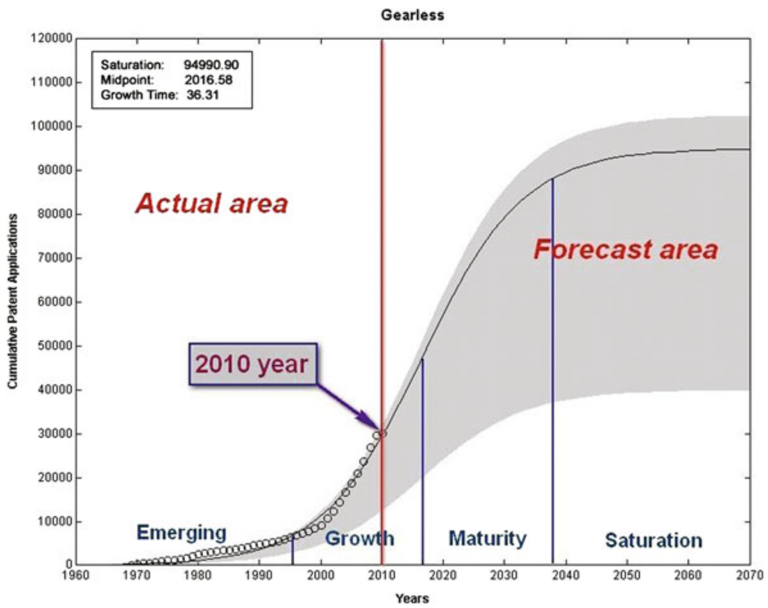


**Fig. 12** Gearless wind turbine growth curve

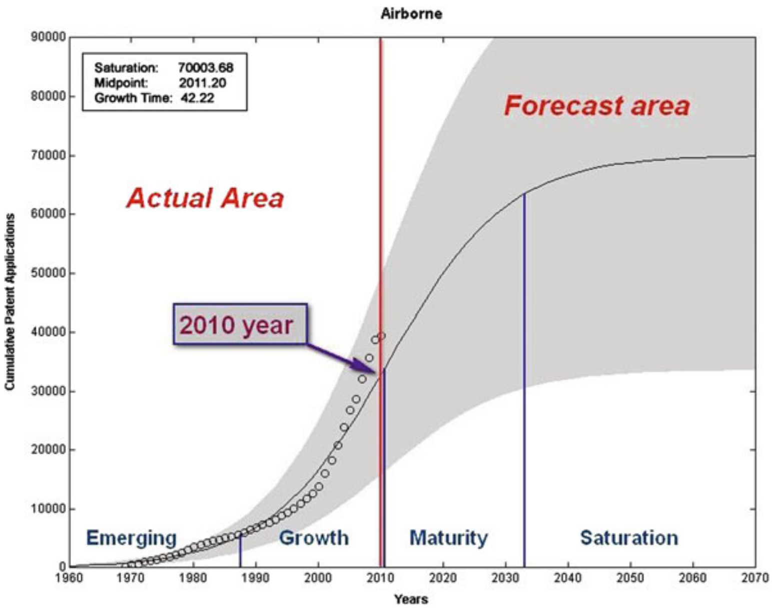


**Fig. 13** Airborne wind turbine growth curve

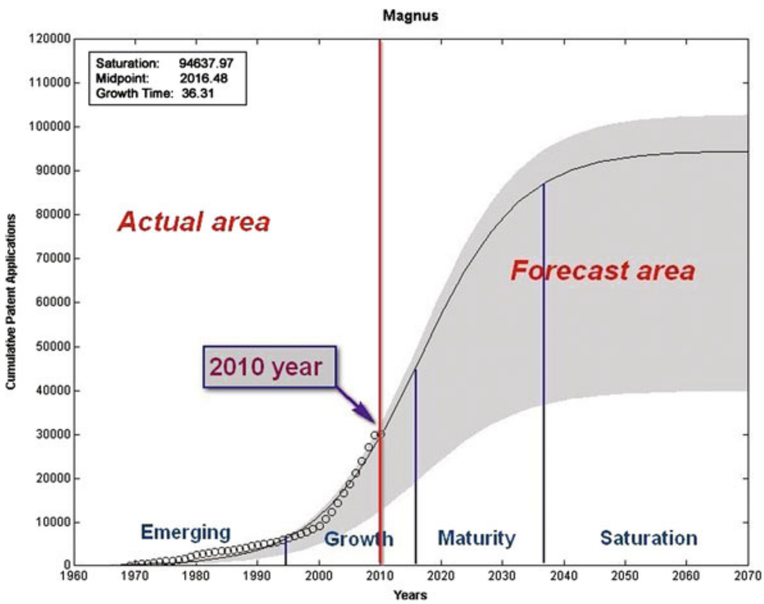


**Fig. 14** Magnus wind turbine growth curve

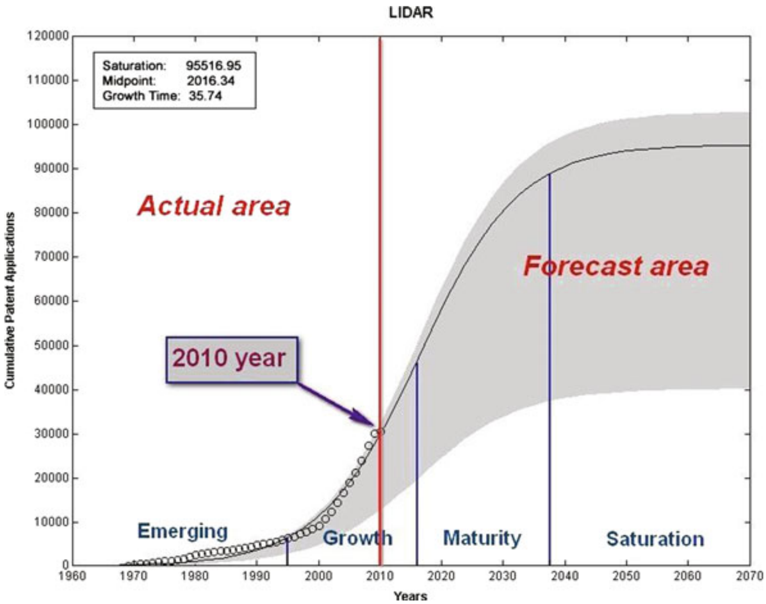


**Fig. 15** LIDAR wind turbine growth curve

very end of growth stage and going to be in maturity stage with midpoint in 2011 and saturation point in 2032. The growth time of jet engine wind turbine, gearless wind turbine, airborne wind turbine, magnus wind turbine and LIDAR wind turbine are 46.42, 36.31, 42.22, 36.31, and 35.74 respectively.

## *4.4 Current Status of Wind Turbine in the Market*

After the forecasting method being applied to all the wind turbines, this sub section is going to find the current status of the wind turbine technology in the Market. There are several companies that are currently developing airborne wind turbine, e.g. Magenn Power, Makani Power and Joby Energy [K41] [K42] [K43]. All of those companies are still in prototype test phase and hope can go into production in the end of 2011. FloDesign is the one that is well-known in developing Jet Engine Wind Turbine. FloDesign is also in prototype phase as of 2010 [K44]. Siemens, Honeywell, GE and AWE are known in their contribution to produce Gearless Wind Turbine [K45] [K46] [K47] [K48]. Currently, Gearless wind turbines are being tested in the field. The mass production should begin as early as 2012. Mecaro is one of many companies that currently focus on Magnus Wind Turbine. Prototype of Magnus Wind Turbine was exhibited at the Philippine 1st Energy Efficiency Forum in 2010 [K49].

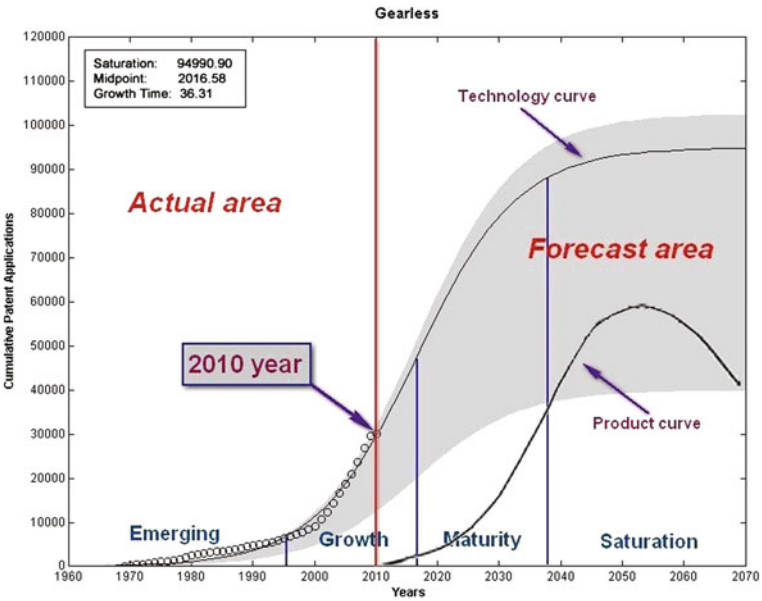


**Fig. 16** Illustration of product development that follow technology development

All the real life applications are consistent with the growth curve for each wind turbine. The current state (2010) of each wind turbine in the growth curve reflects what is currently happening in the market. The product is usually developed once the technology is close to maturity. Without any significant development of the technology, companies usually reluctant to develop to product because companies do not want to waste resources to develop a product that utilizes technology that will never develop. For the illustration, please see Figure 16.

As for LIDAR Wind Turbine, after more research being done, we discovered that LIDAR is not wind turbine that actually produce electricity like other four wind turbines. LIDAR is just a technology that can be embedded in any kind of wind turbine to help wind turbine produce energy more efficiently.

Table 2 below summarizes the current state of the wind turbine technology with the product development in the market.

**Table 2** Summary of wind turbine products in the market according to wind turbine technology

| Type | Company | Product | Prod. Year | Capacity |
|---|---|---|---|---|
| Airborne wind turbine [52–56] | Magenn power | Magenn air rotor system (MARS) | 2010–2011 | 100 Kw |
| | Makani power | Makani M1 | Prototype test flight Oct 2010 | N/A |
| | Joby energy | N/A | Prototype test flight Jun 2010 | N/A |
| | Sky wind power | N/A | N/A | N/A |
| Jet engine wind turbine [57] | FloDesign[1] | Series B | Prototype phase | 150 Kw |
| Gearless wind turbine [58–63] | Siemens[2] | SWT-3.0-101 | First prototype Dec. 2009. Launched Apr 2010 | 3 Mw |
| | Honeywell | WT 6500 | 2010 | 2000 kWh/yr in class 3 winds and up to 2752 kWh/yr in class 4 winds |
| | GE (Scanwind)[3] | N/A | 2012 | 3.5 Mw |
| | AWE[4] | AWE 52–750 | 2010–2011 | 750 KW |
| | | AWE 52–750 | 2010–2011 | 900 KW (rotor 52 m) |
| | | AWE 52–750 | 2010–2011 | 900 KW (rotor 54 m) |
| Magnus wind turbine [64] | Mecaro | Spiral magnus | Spiral magnus tested at NASA wind tunnel Feb. 2007. Prototype of the spiral magnus wind turbine was exhibited at the Philippine 1st energy efficiency forum on July 14, 2010 | 12 Kw |
| LIDAR wind turbine [65, 66] | Pentalum technologies[5] | SpiDAR | The company plans to launch a pilot of its system in early 2011 | N/A |

[1] Flodesign just received $34.5 million in venture capital, along with $8 million in grants from the DOE in 2010, allowing it to begin commercial production on its tested turbine. (currently only prototype)

[2] Siemens show huge interest in Gearless. Prototype installed in Denmark. Siemens Energy sold three of its gearless turbines in the US for the first time in August 2010. Pilot production of the gearless turbines is scheduled to begin next year, with mass production starting in 2012. By 2014, the majority of production should be converted to gearless drive technology

[3] GE purchased company name ScanWind to focus on Gearless type of wind turbine

[4] AWE has started to pursue direct drive (gearless) since 2008 and the mass production will be starting next year (2011)

[5] Pentalum Technologies receives ABB investment in latest financing (news, Nov 17, 2010)

## 5 Conclusion

With the issue of global warming and instability and scarcity of fossil fuels, renewable energy seems to be one promising solution. It is undeniable that wind energy is gaining more attention in the last decade. Wind turbines were developed to produce energy from natural wind power.

This paper builds upon the earlier work published in use of patents [67] and assessment of wind energy [68]. This paper identified 5 emerging technologies in wind turbine, e.g. Jet Engine Wind Turbine, Gearless Wind Turbine, Magnus Wind Turbine, Airborne Wind Turbine and LIDAR Wind Turbine. Technology forecasting methods were applied to find which wind turbine is the contender among others.

Patents data are more comprehensive than publication data. The publication analysis did not give a clear insight of which wind turbine is leading because of limitation of data availability. From patent analysis, the shapes of each wind turbine plot are similar to that of the s-shaped growth curve. The results of growth curve show that jet engine wind turbines are currently in early maturity stage. Meanwhile, gearless wind turbines, LIDAR wind turbines and Magnus wind turbines are at the end of growth curve. Airborne wind turbines are currently in the very end of growth curve and almost move to maturity stage.

Additional research is performed to find the real life application of those wind turbines. All of those wind turbines are not currently being mass produced. Those wind turbines are in prototype phase or field test. The applications of the wind turbines in the market show consistency with the forecasting results. The findings suggest that all of those wind turbines are expected to be produced started in 2011 or 2012 and implemented widely around 2014–2016 which also show the consistency of the growth curves being presented.

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# Technology Adoption: Building IT

**Abdussalam Alawini, Napong Tanatanmatorn, David Tucker, Katherine Tucker and Tugrul Daim**

**Abstract** Even though energy efficiency provides obvious benefits to new or retrofitted buildings and is widely seen as an appropriate approach to handle the increasing energy and the environment problems, the process of getting there is prohibitively complex and full adoption of energy efficiency in new buildings has been low. While the individual level of energy-efficient aspects like appliances and materials are progressing, the aggregate level of integrating these individual pieces to maximize the energy efficiency potential (Green BIM in particular) seems lagging. This chapter then aims to investigate major factors and introduce the use of Agile project management concept to enhance Green BIM adoption while ultimately increasing energy efficiency in new or retrofitted buildings.

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## 1 Introduction

The energy consumption issues of the United States cannot be discussed without the inclusion of the energy needs in the building sector. Currently there are approximately 76 million residential structures and 5 million commercial structures in the United States [1]. As the population grows upward of 311 million people, the need for additional buildings will correspondingly increase [2]. Currently, buildings account for approximately 40 % of total energy and 70 % of electricity usage [3]. Additionally, the cost of energy in the United States has also been increasing. As the rest of world develops and industrializes, the demand for energy is going to increase due to the economic elasticity in the energy sector.

When a consumer builds a structure, there is a formula that goes into the decision for the selection of materials, and construction technique. The formula is very similar to the purchase of goods or services, and can be described as the accumulation of fixed and variable costs. Using this technique the consumer bins the costs of purchasing a product into categories of either fixed cost (costs that are not dependent on usage or level of service) or variable cost (costs that vary with usage level). For example when a contractor is choosing products to occupy a commercial space, they may consider the cost of purchase and the installation cost multiplied by the quantity that is required.

Given the current energy demands of the United States, and rising cost of energy it is in the best interest of companies to decrease the total lifecycle cost for a building and structure. In the building sector the user would take into account the operating cost of a structure with respect to energy usage and efficiency over the total life of the structure. This measure is critical to decreasing total energy usage in the United States because the median lifespan of a building is between 65 and 80 years [4]. Therefore, after a construction decision has been made the next opportunity to integrate a new decision or opportunity to implement an energy efficient option is lost until a replacement is needed. However, during the initial construction of buildings, there are opportunities for increased efficiencies and usage of decision models that encompass the total lifecycle cost.

Additionally, there are normalizing tools that can be used by contractors and builders that can help push industries in the correct path with respect to decision making. Some of these tools are rules of thumb, building codes, and third party certifications (such as LEED). Each of these tools, takes the decision making factors away from the user, and essentially disconnects the decider from the decision drivers. The contractor and architect must be fully engaged in the decision making process, and learn from the collective mistakes of the industry while concurrently striving for improvement. The industry must continually evolve their best practices to achieve the energy efficiency levels required for future efficiency requirements [5].

The growth of the Leadership in Energy and Environmental Design [6] rating system is a prime example of the interest in energy efficiency and environmental responsibility in the built environment. The U.S. Green Building Council's LEED

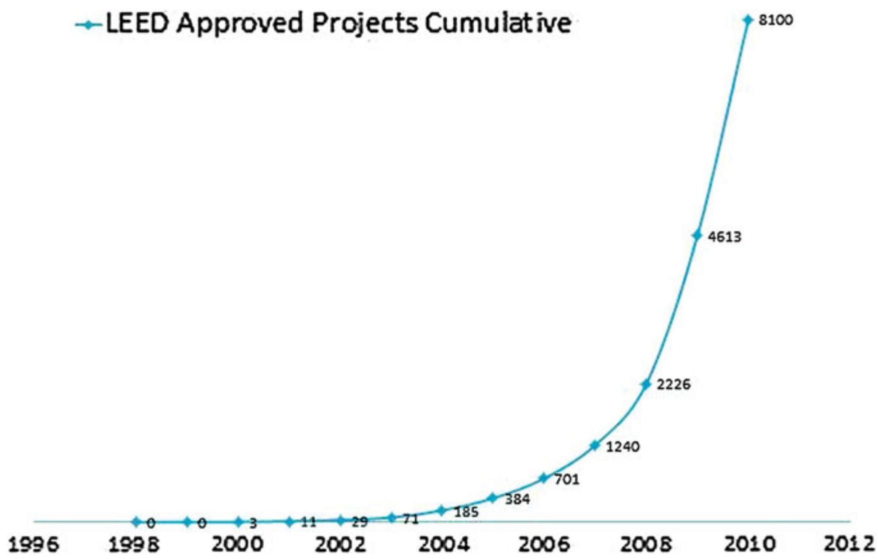



**Fig. 1** LEED adoption

program is indisputably leading in encouraging, evaluating, and recognizing energy efficiency and environmental design. From the inception of the program in 2000 recognition and adoption have been steadily growing. As interest and adoption has grown the rating system has also been evolving to include increasingly more efficient prerequisites and sophisticated technologies.

Figure 1 identifies the growth that LEED certified buildings have grown since the inception of the organization.

Interest in the movement represented by LEED has evolved from novelty to necessity. The relationship between the built environment, energy efficiency and energy generation opportunities fall into the mercy of assisting technologies, specifically the proper utilization of Green BIM software. Such powerful tools will prove to be imperative to future successes.

## 2 Building Information Modeling

Building Information modeling (BIM) is the process of using computer systems to develop computer generated models that can simulate the planning, design, construction, and operation of a building [7]. BIM allows all engineers participating in a construction project to fully and truly construct a building virtually, and in detail. In addition, BIM can be later used by building owners to manage the building throughout its lifecycle.

The use of computer systems is not new in the construction field. Computer aided design (CAD) software is still widely used in generating 2D and 3D designs for buildings. The main difference between BIM and CAD is that CAD describes different building views that are unrelated to each other. So, if one of these views is edited, then all other views must be updated manually, which causes high rates of errors and poor documentation. In addition, data in these CAD designs don't include intelligent semantic data. BIM models make use of object-oriented data structures, famous computer science approach, where objects are defined in terms of building elements and systems [7].

"A building information model characterizes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories and project schedule." [7] As a result, BIM provides an accurate representation of a building in an integrated data environment. With the integrated data environment, communications across different construction teams (such as plumbing, electrical wiring and air conditioning) can be performed in easier and more effective ways. The overall construction processes will be more effective due the accurate (just-in-time) design and cost simulations.

Accordingly the use of BIM eliminates up to 40 % of unplanned changes. The time to generate a cost estimate is reduced by up to 80 %. Additionally, clash detection can save up to 10 % of the contract value [8].

## 3 Green BIM

Green BIM is not a different system from BIM. It is the idea of utilizing BIM tools to develop more sustainable buildings. BIM has powerful analysis and simulation tools that can provide immediate insights into how design decisions may impact building performance during its lifecycle. Energy (performance) analysis, lighting analysis, building form analysis, water harvesting analysis, and renewable energy analysis are some of these analysis tools regarded as Green BIM. Typical CAD designs don't include these analysis tools. As a result, architects use semi-manual approaches to calculate building performance, which may produce inaccurate estimates and cost additional time and money [3].

Green BIM also encourages the process of integrated design which is a critical strategy in making a building greener. Construction projects involve many building sub-systems' designs. With the use of BIM central database, critical design decisions (such as material type and quality) can be optimized based on other sub-systems decisions. This difference significantly improves the performance of buildings that are built using BIM as well as making them more sustainable.

## 4 Adoption of Green BIM

Adoption of Green BIM is a complicated topic to discuss due to the scarcity of information. For example data for Green BIM usage and implementation during the design and construction processes are not available for analysis. Based on this lack of data, it was determined that the adoption of Green BIM could be analyzed utilizing a Biblio-metric analysis. The assumption being, that adoption would exist on an article basis before being accepted by the industry. Appendix A titled *Green BIM Search Criteria* identifies the methodology and search criteria utilized to collect the data analyzed below.

Figure 2 identifies the cumulative interest of Green BIM, and Building Information Modeling Articles that include the topic Energy Efficiency, from articles published online. The Term Building Efficiency was added to figure to compare the topic as a baseline perspective.

As Fig. 2, the interest in building efficiency articles has grown steadily without sign of decreased interest. Essentially, this line indicated that professionals are interested in efficiency. The other two plotted lines in the figure are cumulative Green BIM articles, and articles containing both terms, Building Information Modeling and Energy Efficiency. As indicated by the above figure, the interest these terms is increasing and started in 2004. Based on this data it can be assumed that the interest in Green BIM will continue to grow in the future years.

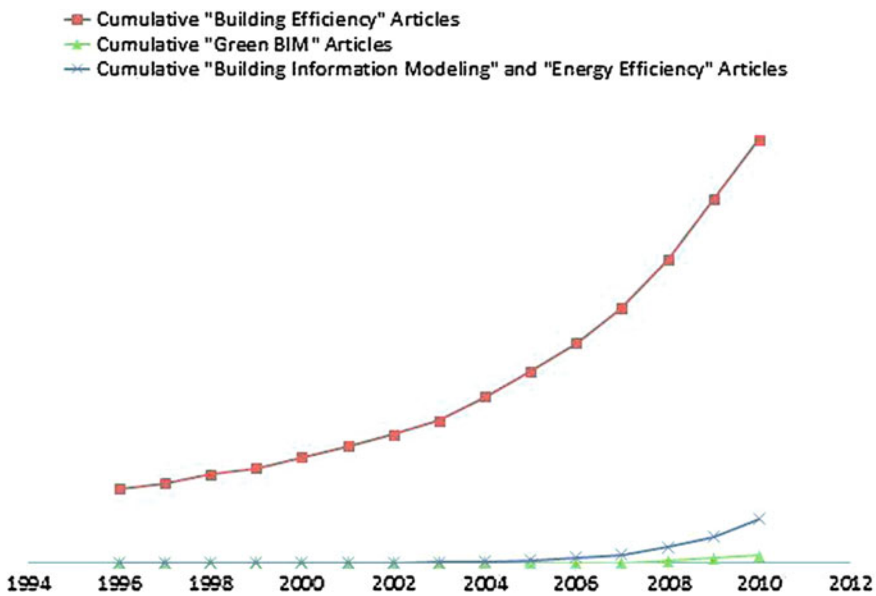



**Fig. 2** Interest in building efficiency and green BIM

To go deeper into the adoption of Green BIM, an analysis of the specific programs is necessary. Currently, there are several prominent programs in this sector. The specific programs analyzed are identified in Table 1.

As Fig. 3, the growth in interest of all the Green BIM software programs has been increasing rapidly since the introduction of the programs. As indicated by the figure, EnergyPlus is exhibiting the largest amount of interest followed by Ecotect. From a market perspective these two programs make up a considerable amount of the interest from academics and publishers with respect to Green BIM.

Currently, the market is on the edge of industry wide adoption of Green BIM tools. A recent survey published by McGraw Hill Construction in the Smart Market Report on Green BIM published the following adoption information [14] (Fig. 4).

This publication is currently forecasting an industry wide adoption with respect to a four year time frame. Although this data paints an extremely optimistic, we believe that the key take away is that Green BIM has a lot of interest from the industry. The same publication also identified a list of drivers for the adoption of Green BIM [14]. The adoption drivers are identified in sequence of importance in the following.

As Table 2, the primary driver for a company to adopt the use of Green BIM software is from the request of the client followed by business related elements, and finally the access to BIM tools. Based on this information it can be justified that any actions that promote multiple drivers will increase the rate of adoption.

**Table 1** Green BIM programs

| Program | Description |
|---|---|
| EnergyPLUS | Energy simulation program that can model heating, cooling, lighting ventilation, and water usage. Software is supported by the Department of Energy and has add-ons to improve usability and functionality [9] |
| Ecotect | Energy simulation program that can model thermal performance, water, solar radiation, shadows and reflections and carbon emission analysis. Software is owned exclusively by Autodesk [10] |
| Green building studio | Energy simulation program that can model natural ventilation, score energy star, day lighting, and weather analysis. Software is owned exclusively by Autodesk and is a Web based program [11] |
| eQuest | Energy simulation program that is designed to be user friendly and free to download and use. Software is maintained by EnerLogic and James J. Hirsch and Associates and is mainly funded by the Department of Energy [12] |
| Climate consultant | Energy simulation program that is specific to the California region, however it can link to EnergyPlus and used in other regions. Software is owned by the University of California Los Angeles [13] |

Each of the above programs were analyzed using a biblio-metric analysis, Fig. 3 illustrates the adoption of the specific programs that are used to complete Green BIM analysis

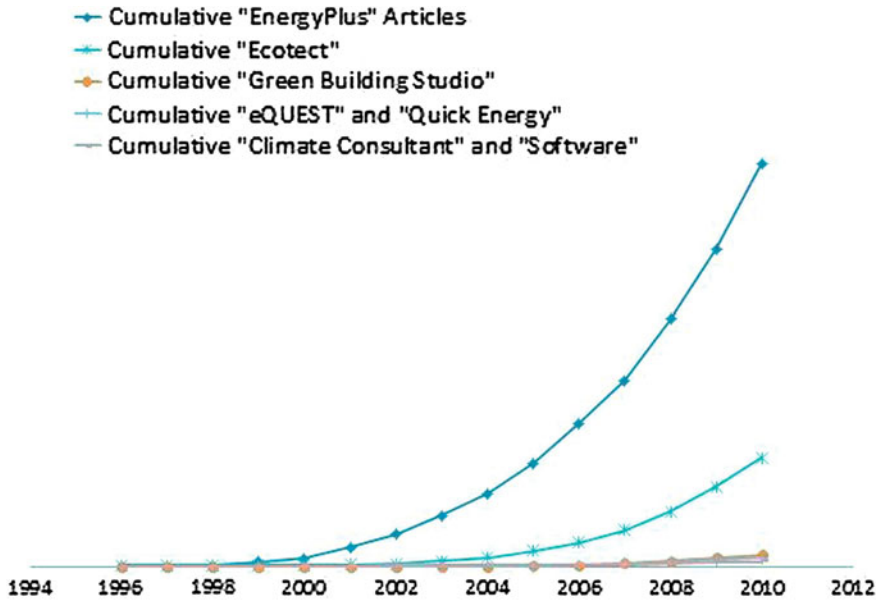
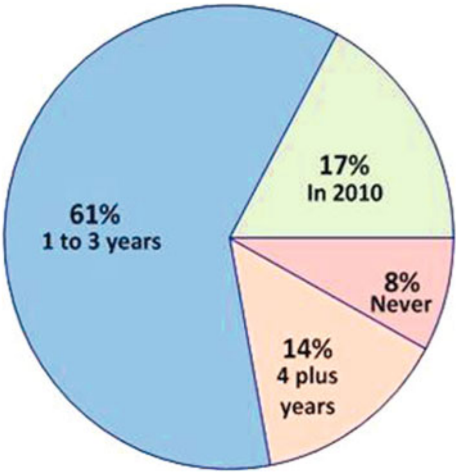



**Fig. 3** Adoption of green BIM software

**Fig. 4** Green BIM adoption statistics




## 4.1 Barriers to BIM and Green BIM Adoption

Despite the productivity and economic benefits of BIM has been increasingly acknowledged and the supporting technology has been rapidly maturing, BIM adoption in the building industry has been slow. It was identified that, besides the technology, the industry nature of being very fragmented and fixed in the work

**Table 2** Green BIM adoption

| Ranking | Percentage | Reason for adopting green BIM |
|---|---|---|
| 1 | >36 | Asked by client |
| 2 | >28 | To be competitive |
| 3 | >18 | Improve ability to do green work |
| 4 | 11 | Generate greater ROI |
| 5 | >7 | Other (i.e. availability of BIM tools) |

process majorly impacts the adoption rate of Green BIM [15]. In this section, barriers to BIM adoption identified according to the industry literatures [15–18] are grouped into 3 categories; technical, organizational, and people/social perspectives.

### 4.1.1 Technical Barriers

Since BIM represents a new technique in dealing with information throughout the building project lifecycle, technological constraint can be viewed as an obvious barrier. According to the literatures, there are two major technical barriers. First, the computability of digital design information is essential in increasing productivity of iterative design process. Digital data used in traditional CAD system is fundamentally based on pictorial data, which is incomputable (despites being digital). The data is meaningful when read by human. However, the computer has no implicit knowledge of the information to be able to understand relationships and automatically calculate the results [14]. Second, the interoperability of the data between different parties is critical to bridge everyone involved in the building process. In addition, since BIM relies on many different purpose-built tools used by different parties, sharing meaningful design information is keyed for BIM to provide useful information flow throughout. Note that interoperability is not just the basic transactional-oriented business IT concept used in other industries like accounting and inventory control system. The application in building industry requires flexibility to deal with complexity of the design and construction process with a lack of fixed business protocols.

### 4.1.2 Organizational Barriers

Current Project Management process for building design and construction that involves collaborations of multiple professionals is identified as one of the major BIM adoption barriers [16]. The current practice is defined as a very mature linear process, which is managed by a series of approval stages involving different functions [17]. Each function is typically from different units in the organization or from different organizations with different and many times conflicting objectives i.e. architects, structural engineers, system engineers, builders, etc. BIM, on the other hand, is introduced to work on the basis of integrated efforts among all parties. Then, there is a barrier of changing how the business has been done for decades to adopt BIM approach. Also, it was identified that there are discontinuities of risks and benefits of each party in BIM adoption that one party experiences a big cost while the other gain the benefits [15]. Thus, without the addressing this important issues, BIM would not be successfully adopted by every key player.

#### 4.1.3 Personal/Social Barriers

People are identified as a major barrier according to the survey conducted in 2008 in the US and UK by Yan et al. [18]. Most of the barrier is to allocate precious time and resources to the training process. Players in the industry including architects and engineers are by nature low margin. They are not willing to invest in BIM if there is not clear evidence of benefit that improves their bottom line profits. This is also consistent with the survey result conducted in Texas by Houston American Institute of Architects, which reported that the lack of experienced personnel, huge learning curve, and time to implement are of primary concerns [19]. In addition, the new BIM process requires changes to what they already are using and good at. There is a natural social and habitual resistance to change, as professionals are satisfied with traditional method to design their projects [18].

### *4.2 Traditional Building Design Process Versus the Old IT Design Process*

One of the major obstacles that faces the adoption of Green BIM is that the current building design “project management” process is linear and mature [17], which inadvertently conflicts with BIM (which is iterative). The principle benefit of BIM is that it overcomes most of the issues resulting from linear models such as communication conflicts and changes in later design stages. Due to the fact that the entire construction business model is based on the linear approach, BIM adoption will be very difficult with the current building design practices [16] (Fig. 5).

In order to overcome this major obstacle, a new design approach that utilizes an integrated design process should be introduced to the construction industry. After meticulous literature research, we found that similar issue was studied and resolved in the software engineering field. Waterfall lifecycle project management was one of the first software development approaches used in the software industry [19]. In this model, the software lifecycle is divided into five stages that are performed sequentially. The model starts with data gathering and analysis, the “requirement” stage, to identify user requirements. These requirements are then used to build the software in the initial design (user interface and database

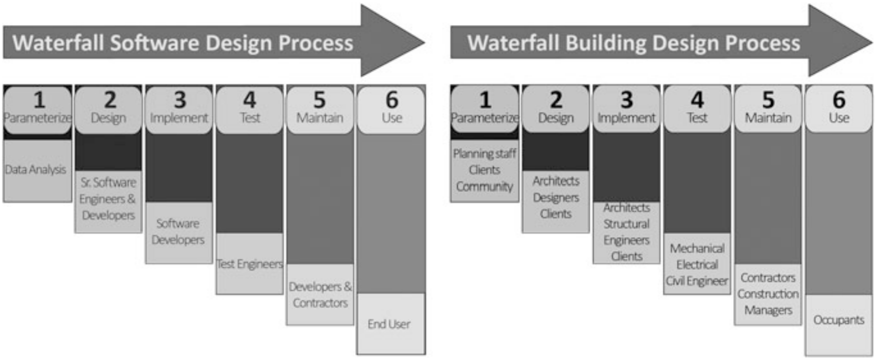



**Fig. 5** Software versus building design process

schema). Then developers will start building the actual product—the "implementation stage". Testing will be performed by a different group of engineers (test engineers) who set different test cases and validate the software results with client requirement. Finally, the maintenance stage which focus on resolving issues that are reported by customer [20].

Waterfall approach has been a good process for linear software development for certain applications that do not require change after their specifications have been defined. However, most software applications today have their specifications redefined during development because of client feedback and/or other factors. As a result, a linear development process, such as the waterfall model, is no longer appropriate. Many approaches were presented as a solution to waterfall model issues, including modified waterfall process, spiral development model, the evolutionary development model and the iterative and incremental approach [19, 20]. However, none of these models were able to achieve the success that Agile development model has achieved. The main reason behind this success is that Agile has changed not only the process of developing software product, but also changed the entire culture and business model around software development [21]. In order to understand how Agile was able to achieve this success, we will discuss Agile development process, understand the key factors of success and apply them to building design process.

## 5 Agile Project Management Overview

Agile is a lifecycle framework for software development processes. It's considered to be a revolution to the traditional development methods, such as Water-fall development process. Agile puts sets of engineering and management principles and techniques in a way that supports rapid and reliable software development. These techniques can handle different scale software projects. This framework fits

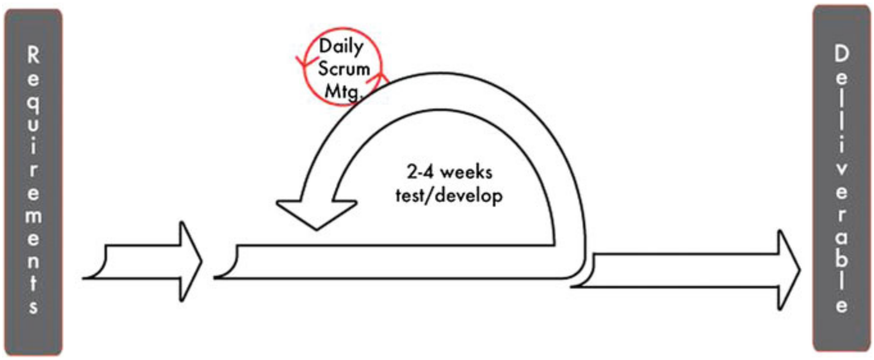



**Fig. 6** Agile

perfectly with application domains that require development to be done in face of ambiguous and rapidly changing of requirements [22].

Since Agile focuses on delivering software products in the fastest reasonable period of time, it provides many evolutionary ideas about how to manage team communications so that it eliminates any extra work that can delay or distract software developers from their main tasks. Customers' involvement during Agile project development stages increases customer satisfaction and decreases change requests in the product lifecycle.

Agile methods agree on the idea of dividing the system features into simpler tasks that could be implemented in iterations. These iterations are delivered to the customer as working releases. The customer has an important role in ordering these tasks according to their business values (Fig. 6).

## *5.1 Design Process Analysis*

From the previous sections, we see that Green BIM is a great new tool that was created to help the building design industry efficiently integrate sustainable components (especially in energy efficiency application) into the building project lifecycle. However, the full capability of Green BIM (and BIM in general) is underutilized, which results in its having disappointing efficiency and full potentials unrealized [23]. Different barriers contribute to the poor adoption and underutilization at different degrees. Among the identified barriers, the traditional linear building design and project management process is identified to have major impacts on the adoption and utilization of Green BIM [3]. As a result, the industry needs an integrated process that optimizes the use of Green BIM across all disciplines and activities ranging from planning and design to construction and operation [3, 23, 24]. The new process should be able to engage Green BIM not only in visualization of design interferences, but also in impacts of design

**Table 3** Framework comparison

| Referenced framework: BIM-optimized work procedures (technology-enabled integrated practice model) | Traditional (linear) | Agile |
|---|---|---|
| Accelerated decision making (front-loaded) for all disciplines | a | c |
| Front-end involvement of stakeholders | b | c |
| Collaborative concurrent process (overlapping phases) | a | c |
| Task-based (not deliverable-based) focus | a | c |
| Schedule compression | a | b |
| Increased sharing of common sets of information | a | c |
| Reduced constr. change orders (design-related coordination Issues) | a | b |
| Reduced client-generated review comments | a | c |
| Reduced internal quality control review comments | a | b |

*Note* [a] level of agreement with the referenced framework, [b] least, [c] most agreed

decisions on construction, commissioning, close-out, and operation and maintenance activities (Table 3).

This section considers the traditional linear design process and the proposed Agile framework with respect to the preferred BIM-optimized work procedures. The characteristics of the Technology-Enabled Integrated Practice Model presented by McDuffie [13] and the framework by Yudelson [24] are used as basis of comparison. The comparisons are shown in the above table. The results show that Agile satisfied all important dimensions of the preferred characteristics of the integrated design framework and that it has a great potential in being applied in the building design industry.

## 5.2 *Agile Applied to Building Design Process*

Due the nature of architectural design, adopting the Agile management methods in the architectural design management strategy would lead to better resource conservation, design integration, and increased client satisfaction. Similar to the software design process, the architectural design process early requirements are sometimes undefined and plans need to be flexible to accommodate necessary changes (Fig. 7).

Incorporating the Agile methodology would allow for the early framework of the project to begin production, while iterative and incremental steps are developed for future implementation. Similar to Agile for software development, Agile for architectural development starts with all known requirements, resources, goals, and parameters.

From there, an architectural design will typically start addressing site issues such as building orientation opportunities and challenges. Green BIM programs offer designers the opportunity to analyze site conditions and simulate the building placement and orientation. These relatively fast feedbacks allow the designer to make changes, consult the client with measurable and options, and adjust the

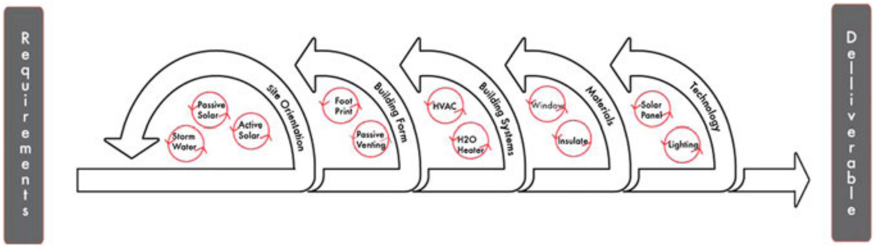



**Fig. 7** Agile architecture

design as it relates to the site. This can lead to the absolute best placement and orientation of the building for the maximization of passive building system efficiency (i.e. increased day lighting, season dependent decreased and increased solar gain, and water management).

Once the site orientation is determined the green BIM software will also assist in designing the form of the building. Building form will have much impact on the efficiency of the passive opportunities inherent in the site and environment. This sprint cycle often analyzes the best size for a roof overhang, window sizes and placements, and efficiencies of various footprint sizes. With client involvement a form can be decided. This step may or may not require another site-based sprint to reevaluate the placement and orientation.

Building systems, such as heating-ventilation-air conditioning (HVAC), waste water management, irrigation management, storm water management, and on-site energy generation systems are each their own sprint, which can be run simultaneously or in an order. Running system options through the green BIM software will help in determining the most efficient options. Keeping in mind that each building-system sprint will inform other building-system sprints, a larger sprint should be run to analyze the combination of all of the building systems working in concert. This may lead to the revisiting of the building form analysis depending on the options determined by the designer and client.

Material and Technology options are the most often changing and updated. Technologies such as Energy Star products, CFL lighting options, and motion sensor switches are examples of ever expanding and increasingly sophisticated options to keep building energy consumption to a minimum. To determine the lifecycle costs for analysis in determining future returns on investment can be quickly and efficiently determined by green BIM software. Material-selection sprints are similarly used to quickly determine combined insulation values of material choice and light absorption/reflection. These options can be again, quickly analyzed, ROI determined and presented to the client.

Along the way production can easily begin regardless of the lack of completeness in the plans. As options are decided on an analysis of the chance for future change will determine whether or not it would be appropriate to begin on that phase of production. It is unlikely that choosing lighting options for an office will chance the building orientation on a site. It would be safe to begin site work while the client and designers are looking at materials and technology. Choosing an energy generation option might change the form of the building slightly to accommodate the feature. If there is a possibility of opting for energy generation the building frame should not begin production until the energy generation sprints have been completed.

Client involvements in architectural design processes vary depending on the client, the designer, expectations, and project scope. The Agile methodologies, with high levels of client feedback and consultation coupled with green BIM modeling will insure success and efficiency in production and product lifecycle. High client buy-in of the process and the project and the implementation of the steps laid out above will result in energy savings, resource savings, design integration, adaptability to changes, and high client and tenant satisfaction.

The adoption of Agile methodology to the architecture industry would promote three of the key drivers that were identified earlier. For instance it would enhance ROI for companies because the operations should increase in efficiency. The companies would have an advantage over their competition therefore they would be more competitive. And the simulation process could be used to market the companies' competency regarding energy efficiency evaluation.

## 6 Conclusion

Introducing a building energy efficiency and sustainability concept, a new discipline that highly involves iterations and various project components, to the fragmented and linear practice process is not a simply straight forward task. New technology, Green BIM in this case, was invented to aid professionals in the building industry to incorporate such new discipline into the building project lifecycle.

Green BIM adoption is forecasted to be picking up in the near future by the industry optimists and our biblio-metric analysis, but a number of adoption barriers still exist. Among those barriers, the linear building practice is identified as a major barrier that causes disappointing results and inhibits the full potential of Green BIM technology.

It is noted that adoption rate would increase if value is realized. Then, the academic and industry literatures emphasize the need for a move from the existing linear building process to the integrated work procedures. Efficiency of the integrated work process in the early planning and design stages that result in improved overall project lifecycle encourage true value of Green BIM to be fully recognized by owners and professionals in the building industry.

The characteristics of the desired procedures of Agile methodology, to which the information system industry has successfully moved from the linear work process. With the objective of optimizing Green BIM value, combining Agile methodology with traditional design practices and the use of Green BIM can bring meaningful implication to the building industry.

Agile methodology requires major changes in work procedures in the building industry which is considered a big challenge. Also, the difference in the nature of the building and the information system industry does not allow a direct translation of successful adoption and performance of Agile methodology in the building industry. However, the Agile adoption experience from the information systems industry can provide significant insight to the key factors considered and implementation techniques to successfully launch Agile in the building industries context.

## Appendix A: Green BIM Article Data

In order to understand the future and adoption of Green BIM, an article search was conducted using data that is available on the Internet. The search engine that was used to data mine the information was Google Scholar. Through Google Scholar, data was collected using the following search criteria (Table A.1):

**Table A.1 Article search criteria**

| Find results: with all the words | Date start | Date end |
|---|---|---|
| "Building Efficiency" | January | December |
| "Green BIM" | January | December |
| EnergyPlus | January | December |
| Ecotect | January | December |
| eQuest and "Quick Energy" | January | December |
| "Climate Consultant" and Software | January | December |

For each of the above searches the years that were analyzed were from year 1996 to 2010. For each of the samples the issue date was changed for both the Start and End values to represent the year of interest. For each of the samples, the number of articles available was recorded in the responding data set.

To determine the Y-intercept of the data, start date was removed and the search year was changed to 1995. This procedure output the total articles that were available before the specified search window. The only search term that this technique was relevant for was, Building Efficiency, because all of the other terms and ideas were created during the specified time frame.

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# Adoption of Energy Efficiency Technologies: A Review of Behavioral Theories for the Case of LED Lighting

**Kelly Cowan and Tugrul Daim**

**Abstract** What factors are most significant in understanding adoption behavior for energy efficiency technologies by commercial, residential, and industrial customers? The case of energy efficient lighting technologies is specifically examined. Several types of lighting technologies are compared to indoor LED lighting to determine how the technology meets the needs of the various user types. What factors are most significant in motivating technology adoption for such technologies, and preventing subsequent technology disadoption? This is particularly important for energy efficient lighting technologies, as both technology adoption and technology disadoption can be extremely rapid, and ongoing user involvement is often required to recognize full benefits from these technologies. The Unified Theory of Acceptance and Use of Technology (UTAUT) is useful in explaining adoption behavior related to stakeholder expectation and buy-in for the new technologies. UTAUT contains four elements that can be adapted to fit this research: (1) Performance Expectancy; (2) Effort Expectancy; (3) Social Influences; and (4) Facilitating Conditions. In the case of energy efficient lighting adoption, and LED adoption in particular, performance expectancy and effort expectancy can be related to factors such as future energy price expectancies, actual savings results, and ease of energy savings. Factors involving social influences include perceptions of environmental friendliness among different user groups, and facilitating conditions include policies, incentives, and educational programs to encourage adoption. Some conclusions are then drawn regarding adoption factors for emerging energy efficient lighting technologies.

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# 1 Introduction

## *1.1 Problem Statements*

What factors are most significant in motivating technology adoption for energy efficiency technologies, and preventing subsequent technology disadoption? The later issue is particularly important for energy efficiency technologies, as both technology adoption and technology disadoption can be particularly rapid for these technologies, and ongoing user involvement is often required to recognize full benefits from adoption. Thus, it is important to study this form of technology adoption from a behavioral perspective to enhance current understanding of which factors are most important in motivating ongoing adoption. It is also important to be able to understand how these adoption factors affect specific user types. Commercial, residential, and industrial consumers are the main user types for energy efficiency technology. Of these user types, commercial users have the highest percentage of electricity use for lighting purposes. Commercial users will be the primary focus of this study, in order to obtain a detailed understanding of the factors affecting this largest segment of energy efficient lighting technology users.

To make this research manageable, it will focus on a special case of energy efficiency technology adoption regarding energy-saving solid-state lighting, which is produced by light emitting diodes, otherwise known as LEDs. The research will examine indoor solid state lighting to determine how well the technology fits the needs of the main user types. Conclusions can then be drawn regarding implications of this research for other examples of energy efficiency technology adoption.

## *1.2 Research Problem Description*

The following section describes the current state of knowledge regarding this problem that has emerged from the academic literature. The Unified Theory of Acceptance and Use of Technology (UTAUT) is a key technology adoption theory that can be used for explaining adoption behavior related to stakeholder expectation and buy-in for the new technologies. UTAUT contains four elements that can be adapted to fit this research: (1) Performance Expectancy; (2) Effort Expectancy; (3) Social Influences; and (4) Facilitating Conditions. In the case of adoption of energy efficiency technologies, performance expectancy and effort expectancy can be related to factors such as future energy price expectancies, actual savings results, and ease of energy savings. Factors involving social influences include various perceptions of environmental friendliness among different user groups, and facilitating conditions include policies, incentives, and educational programs to encourage adoption.

### 1.2.1 Research Questions

Which adoption factors are most commonly cited in the literature on energy efficient lighting technologies?

Are there differences in the most commonly cited adoption factors for commercial, residential, and industrial users?

### 1.2.2 Significance of the Research

This research can provide insights regarding which factors are most likely to promote adoption of energy efficient lighting technologies, such as solid-state lighting. This can inform product design, as well as promotion, and business models that encourage adoption. It also has application to the development of policies to promote energy efficient lighting technology adoption.

# 2 Literature Review

## *2.1 History of Solid State Lighting Technologies*

In 2008, lighting consumed approximately 17 % of total electricity usage in the United States [1]. Table 1 summarizes electricity use for the three key categories of lighting users.

While the residential sector is the largest in terms of total electricity used, only about 16 % of it goes toward lighting. The commercial sector consumes a much higher percentage, with approximately one quarter going to meet its lighting needs. Thus, electricity for lighting by commercial users is about 51 % higher than that of residential users. The industrial sector consumes about 3–5 times less electricity for lighting than commercial and residential users respectively, even though its total use of electricity is similar to the other sectors. In the future, transportation may constitute a fourth sector of electricity use, especially as the trend toward vehicle electrification continues. However, it currently consumes

**Table 1** Percentage of US electrical use for lighting by sector

| | Electrical use by sector (GWh/year) | Percentage of electrical use by sector for lighting (%) | Total electrical use for lighting (GWh/year) | Percentage of total US electrical use for lighting (%) |
|---|---|---|---|---|
| Residential | 1,390,650 | 16 | 222,504 | 6 |
| Commercial | 1,343,200 | 25 | 335,800 | 9 |
| Industrial | 1,003,750 | 7 | 70,263 | 2 |
| Total usage | 3,737,600 | | 628,567 | 17 |

*Sources* Calculated from Energy Information Administration (EIA) 2008 [1], and Shively 2008 [2] only 0.1 % of total US electrical load, so it was not included in this research at the present time.

Given the amounts of electricity used for lighting in the commercial, residential, and industrial sectors, new energy saving lighting technologies have the potential to produce significant reductions in overall electricity usage. A number of emerging technologies appear promising for improving the efficiency of lighting technologies. Additional benefits to new lighting technologies include significantly longer service lifetimes, which reduce the need to replace bulbs, reduce the amount of electronics waste generated, and lower total cost of ownership (TCO).

One of the most rapidly developing new technologies for energy efficiency lighting technology is the light emitting diode, or LED. Currently, most LEDs produce under 100 Lm/W [3]. However, prototypes exist which produce over 200 Lm/W, and there are expectations of up to 280 Lm/W by 2015 [4]. Incandescent lights, the long-time dominant technology, typically produce only about 20 Lm/W [4]. Fluorescent lights are another well developed competing technology, especially in the commercial sector. They currently are less expensive than LEDs and produce up to 125 Lm/W [5]. However, fluorescent lights appear to be nearing the limits of their technical capabilities, and are not expected to improve significantly in coming years, as shown by Fig. 1. Furthermore, the service lifetimes for LEDs range from about 25,000 to 100,000 h [6]. This compares to only about 1,000–2,000 h for incandescents and 8,000–10,000 h for fluorescents [4].

LED lighting technologies offer a number of additional advantages, as well as certain disadvantages. Table 2 provides some additional details regarding the pros and cons of LEDs.

A number of questions remain regarding how rapidly LEDs and other energy efficient lighting technologies will be adopted. Much of this depends on the rate at which these technologies improve and costs are reduced. However, a great deal of the decision regarding the rate at which users adopt these technologies also depends upon specific factors regarding the type of end-user adopting the technology, the factors each user type considers important, and the level of importance and/or expectation that users associate with these factors. Several recent studies have examined these factors in relation to adoption of energy efficiency technologies in general, and to lighting technologies in particular.

Andrews and Krogmann used logistic regression modeling to analyze the adoption of energy efficiency technologies for commercial buildings in 2008 and found that locational factors, building use factors, and building-specific characteristics explained most of the adoption patterns for the leading energy efficiency technologies [9]. However, they concluded that their model only weakly explained the adoption of lighting technologies. Installation costs, energy prices, evolving standards, and other performance-related factors regarding new lighting technologies, which are just beginning to challenge the dominance of existing lighting technologies in the commercial sector, appear to have been major reasons why many users were reluctant to adopt these technologies. Unless decision makers were willing to incur large up front costs, typically in newer, owner-occupied buildings, it was found that they were unlikely to adopt advanced new lighting

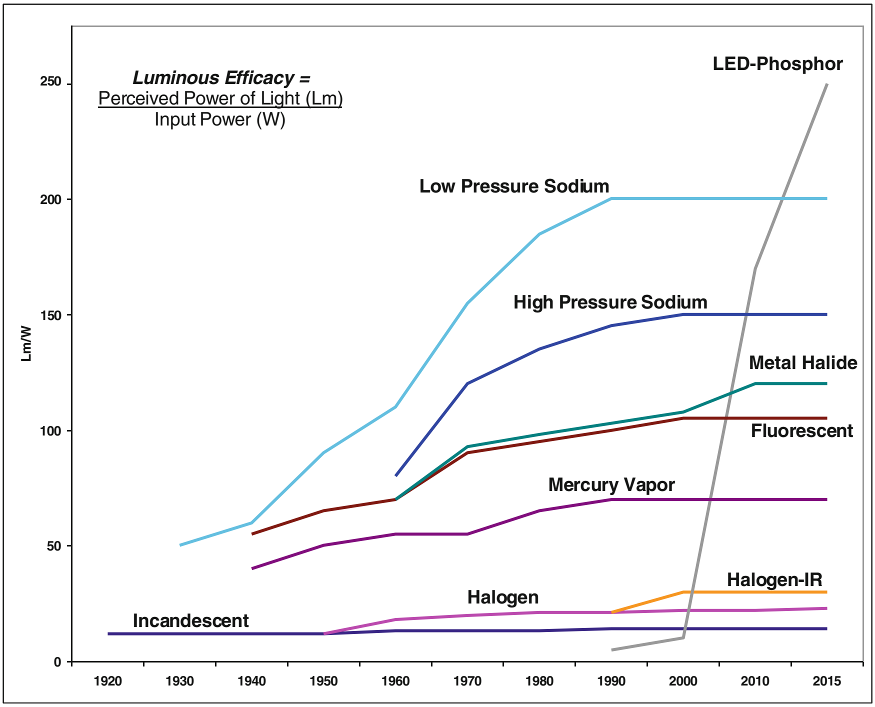


**Fig. 1** Trend in efficacy of illumination technologies (Adapted from UCSB [4])

systems, largely due to the fact that it was unclear they would receive enough payback from savings on energy prices.

Anderson and Newell also examined the adoption of energy efficiency technologies in industrial manufacturing environments using similar logit modeling techniques and found adoption rates to be highest for projects with shorter payback times, lower costs, greater annual savings, higher energy prices, and greater energy conservation [10]. Manufacturing plants were 40 % more responsive to upfront costs versus annual energy savings. Therefore, subsidies were seen as a more effective policy instrument to promote adoption, rather than energy price increases. Fairly high hurdle rates of 50–100 % were found for investments in such projects.

Regarding energy efficiency adoption for residential users, Caird et al. also found considerable obstacles to the adoption of such technologies in UK households [11]. Even among environmentally conscious consumers, only about one-fifth of those who had seriously considered energy efficiency adoption actually reported having done so. Most who had adopted energy efficiency lighting technology had chosen compact fluorescent lights, and all but 7 % of the sample said that high prices and lack of information about LEDs had prevented them from adopting this technology. Some evidence also suggested that for environmentally conscious consumers, the adoption of high profile renewable energy technologies, such as solar panels, may confer a higher status than the adoption of more mundane and generally invisible

**Table 2** Advantages and disadvantages of LED lighting technologies

| Advantages | Disadvantages |
|---|---|
| *Efficiency*. LEDs can produce more light per watt than incandescents and many fluorescent bulbs. Their theoretical maximum efficiency is higher than any other current lighting technologies. Shape and size does not affect efficiency, unlike fluorescent bulbs. LEDs also radiate very little heat compared to incandescents and fluorescents | *Efficiency*. Although LEDs theoretical maximum efficiencies are very high, currently fluorescent bulbs are more efficient at producing light in the commonly desired daylight spectrum ranges |
| *Lifetime*. LEDs useful operating lives are estimated between about 25,000–50,000 h today to 100,000 h or more in the future. of useful life, though time to complete failure may be longer. Incandescent light bulbs last only about 1,000–2,000 h, while most fluorescents last about 8,000–10,000 h. LEDs also tend to slowly grow dimmer over time, rather than abruptly failing, like most other lighting technologies | *High Purchase Price*. The initial price of LED lighting is still considerably more expensive than other lighting technologies, however costs are projected to fall rapidly. The high energy efficiency of LEDs currently does not offset the higher purchase costs |
| *Color*. LEDs can produce colored light without the use of filters. Most current LEDs tend to produce cooler colors, however, than traditional light sources, leading some people not to choose LEDs for general illumination | *Light Quality*. The color spectra produced by LEDs can differ significantly from sunlight or incandescent light. The color of the light tends to be cooler and more blue. Although advances are being rapidly made to develop LEDs which produce natural light colors, it is unclear when such changes may occur |
| *Cycling*. LEDs can be turned on and off very quickly, and frequently cycling them does not cause premature failure, the way it does with fluorescents | |
| *Low Toxicity*. LEDs do not contain toxins like mercury that are found in fluorescent bulbs. This makes recycling easier | |

*Sources* EERE [6], DoE [3], Azevedo [7], Mehta [8]

technologies associated with energy efficiency. Other surveys in the UK [12], and in the US [13] have also pointed to concern among potential adopters of residential energy efficiency technologies to avoid uncertainty before making major investment related to energy savings. One encouraging trend that emerged, however, from these studies was that many homeowners seemed committed to reducing energy use, and simple actions and/or behavioral changes to save energy. Nair et al. also found that among customers who perceived high energy prices to be a major problem, there was a much higher likelihood they would invest in energy efficiency technologies [14].

This research seeks to identify what is currently know about the most common factors influencing the adoption patterns of energy efficiency technologies in general and energy efficient lighting technologies in particular for commercial, residential, and industrial users. However, first, it is important to clarify several background points regarding the subjects of energy efficiency and energy conservation, as well as relevant theories regarding the adoption of technology. Behavioral theories of technology acceptance and use will be specifically considered, since energy efficiency technologies often require extensive understanding of user perceptions, both before and after adoption. Caird points out that there has been a lack of research on how energy efficiency technologies are actually used by consumers [11]. Without a full understanding of these processes and motivations, there is a risk that users who have adopted energy efficiency technologies may later choose to reject, or disadopt them. This research will examine such behavioral factors in order to get a better understanding of what influences the acceptance and use of such technologies.

### *2.2 Energy Efficiency and Energy Conservation Technologies*

Energy efficiency involves decreasing the amount of energy input required to achieve a unit of desired output, such as light, heat, or other useful functions [2]. The goal of energy efficiency programs and technologies is to enable the effective use of energy to create products, perform work, and achieve all the necessary goals for which energy use is required, while minimizing the amount of energy that is wasted in the process. Another way of expressing this is to say that energy efficiency reduces the energy intensity of processes. Energy conservation is a closely related concept, but it seeks to reduce the total amount of energy consumed, rather than trying to increase the effectiveness with which it is used [15]. Energy efficiency and energy conservation are often used in concert with one another and can be important components of strategies to insure adequate energy supplies are available to meet the needs of growing populations. In practice, the terms energy efficiency and energy conservation are often used interchangeably, since there are often significant overlaps in these functions. For the purposes of this paper, energy efficiency will be the preferred term. Energy efficiency is also considered a form of alternative energy, since it is an alternative to building and using conventional energy sources, such as fossil fuel-based power generation.

Policies and programs to promote the adoption of energy efficiency technologies and practices have a long history. Many countries around the world established energy efficiency and energy conservation programs starting after the 1970's oil crisis. According to a report by the International Energy Agency (IEA), without the energy savings that have been achieved since 1973, the total amount of energy required in 1998 would have been at least 50 % higher [16, 17]. The agency further predicts that future growth rate of world energy consumption can be cut another 50 % by 2030, using new and existing energy efficiency and energy conservation technologies. Figure 1 summarizes the expected improvement of the various types of energy efficiency lighting technology by 2015 [18].

Energy efficient lighting technologies appear to offer significant potential for improvement in the near future. Figure 1 shows that LEDs offer the greatest potential for improving the amount of light output produced per unit of energy used. Thus, the adoption of LEDs offers an opportunity for major saving in the energy needed for lighting, and could play an important part in future efforts to shrink the growth of energy use. However, in order to better understand this opportunity, it is important to examine how the process of technology adoption works.

## *2.3 Theories of Technology Adoption*

In order for a new technology to be utilized, an innovation-decision process must occur whereby the individual or decision-making unit moves from the point of first knowledge of a technology to a decision to accept and implement the innovation. Rogers defines technology adoption as the stage in the innovation-decision process where the choice is made to "make full use of the innovation as the best course of action available [19, 20]." Rogers further defines five stages in the adoption process: (1) Knowledge; (2) Persuasion; (3) Decision; (4) Implementation; and (4) Confirmation [21]. An individual may choose **not** to adopt an innovation at any stage in this process, including disadopting an innovation after initially accepting it.

The issue of disadoption is particularly important for energy efficiency technologies. Many energy efficiency technologies are high involvement products that require considerable ongoing commitment by users after the initial adoption decision, in order to continue receiving the benefits the technologies confer. While this may not be true of simple, low cost interventions like weather proofing a house, more advanced energy efficiency products often involve larger investments, longer time to learn how to use them, customized them, and/or decide if the user is willing to continue accepting the performance factors of the new technology in return for the tradeoff of energy savings. An advantage of energy efficiency technologies is that many of them can be adopted very rapidly. This can occur, for example, as quickly as it takes to put in a new light bulb. At the point where a decision has been made to retain energy efficiency technologies, the energy saving benefits continue to occur constantly and permanently, unless a disadoption occurs.

Technology adoption is a process which can occur through a variety of mechanisms. The Technology Adoption Lifecycle [22], originally developed as a sociological model, examines how information about novel products, or ideas, can spread throughout a network of potential adopters. The model was later generalized in Roger's widely read textbook, *Diffusion of Innovations* [19]. The Bass Model of Diffusion [23] is another common method for studying the introduction of new products by forecasting adoption based on coefficients of innovation and imitation.

The Theory of Reasoned Action (TRA) [24] examines adoption from a behaviorist perspective, proposing that "the individual's positive or negative feelings about performing a behavior" create a behavioral intention, which is comprised of attitudes and subjective norms regarding the behavior for the individual's social group. A diagram of this model is provided in Fig. 2.

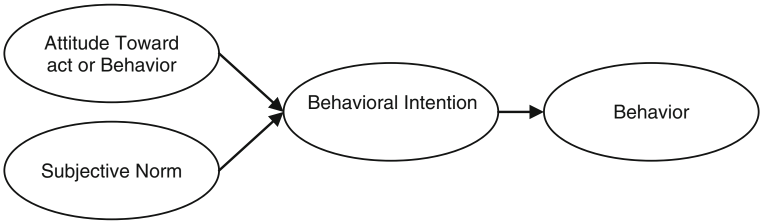


**Fig. 2** Theory of reasoned action (Adapted from [24])

The Theory of Planned Behavior (TPB) [25] addresses a number of limitations of TRA, such as overlap between attitudes and norms, and adds the dimension of perceived behavioral control, which contributes to actual behavior. Decomposed TPB (DTPB) [26], further breaks down the precursors which lead to the variables of attitude, subjective norms, and perceived behavior control. The Technology Acceptance Model (TAM) [27, 28] also deals with limitations of TRA by identifying perceived ease of use and perceived usefulness of technology as factors which contribute to the formation of an attitude, and ultimately a behavior. The model was extended as TAM2 [29, 30]. A diagram of this model is provided in Fig. 3.

TAM was refined into a new theory called the Unified Theory of Acceptance and Use of Technology (UTAUT) [31, 32], which includes the elements of performance expectancy, effort expectancy, social influence, and facilitating conditions. A diagram of this theory is provided in Fig. 4.

UTAUT has largely been applied to projects involving the implementation of Information and Communication Technologies (ICT). User participation in new ICT systems after implementation is critical, just as it is with energy efficiency technologies, in order to realize the full benefit of the system. Attitudes within a social network are also important in determining continued use of a system. As previously noted by Nair et al., social effects, including status and prestige, can also be relevant to the adoption of energy efficiency technology [14]. Perceptions regarding needs, such as views on the need for a new ICT system, or views regarding the high cost of energy, can drive buy-in by potential adopters on the choice of a solution to meet those needs. Likewise, expectations on the

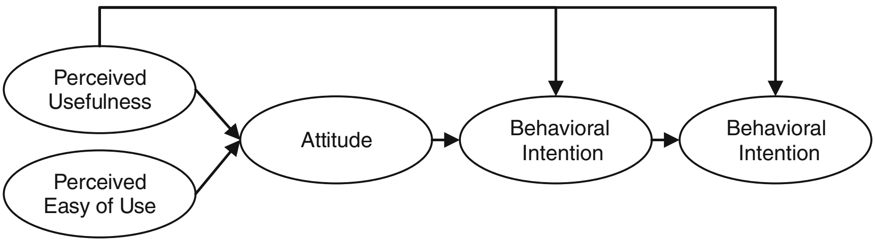


**Fig. 3** Technology acceptance model (Adapted from [27, 28])

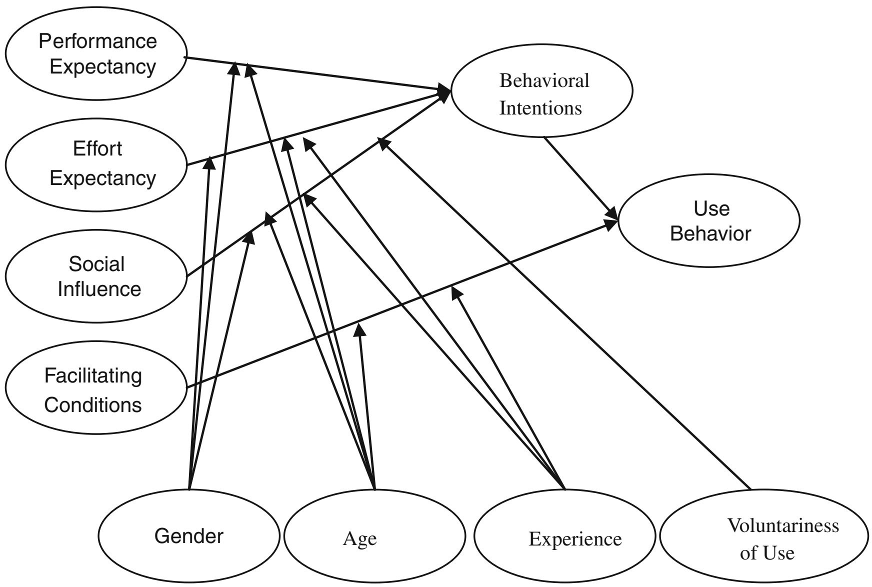


**Fig. 4** Unified theory of acceptance and use of technology (Adapted from [31, 32])

performance and quality of a solution can influence adoption for both ICT and energy efficiency. Thus, UTAUT appears to have strong applicability for energy efficiency technologies.

## 3 Model Development

To better understand the application of behavioral adoption theories, such as UTAUT, to energy efficient lighting technologies, and to determine which factors are most commonly cited as significant in influencing adoption for each user type, a literature review was performed. To identify these factors, a search of academic articles was conducted in the Compendex database for terms related to "technology adoption" and "energy efficiency." The search was further narrowed to articles involving lighting technologies. This initial search resulted in 79 articles relating to these topics. After careful review, however, 49 articles were selected that were deemed to be specific and relevant enough to the exact topic of this research to be included in this analysis. Adoption factors identified from the literature on energy efficient lighting technology are summarized in Table 3. They have also been categorized according to the four elements of UTAUT.

References in the literature are given next to each of the adoption factors in the table. The research questions below then focus in on the following aspects of energy efficient lighting technologies:

**Table 3** Factors driving technology acceptance and use of EE lighting by behavioral category

| Behavioral category | | Technology acceptance and use factors |
|---|---|---|
| Performance expectancy | Relative advantage and outcome expectations | Installation cost [7, 33–38] |
| | | Energy cost savings [7, 33, 35, 37–45] |
| | | Payback time [35, 46] |
| | | Maintenance cost [39, 47, 48] |
| | | Total cost of ownership [7, 9, 33, 38, 39, 41, 42, 45, 47–52] |
| | Perceived usefulness and fitness for purpose | Brightness [37, 45, 53] |
| | | Light color [7, 41, 54, 55] |
| | | Start-up speed [38, 42, 45] |
| | | Flicker [41, 55] |
| Effort expectancy | Ease of operation | Ease of use [52, 54, 56, 57] |
| | | Ease of maintenance [38, 42, 58] |
| | | Ease of recyclability [34, 41, 59] |
| Social influences | Subjective norms and image | Perceived greenness of product [7, 9–14, 33, 34, 48, 59–61] |
| | | Social Status/Significance of Adoption [8, 33, 36, 39, 52, 56, 62, 63] |
| | | Importance of recyclability [34, 41] |
| Facilitating conditions | Compatibility | Standards/Compatibility [47, 57, 64] |
| | | Recycling infrastructure [34, 35, 38] |
| | Perceived behavioral control | Taxes or tariffs [39] |
| | | Energy prices [40, 65] |
| | | Incentives or promotional policies [40, 48, 57, 63] |
| | | Public environmental consciousness [9, 41, 56, 59, 66] |

Which adoption factors are most commonly cited in the literature on energy efficient lighting technologies?

Are there differences in the most commonly cited adoption factors for commercial, residential, and industrial users?

Each category of these adoption factors is described below. An explanation is then provided for how each of these factors relate to technology adoption for energy efficient lighting technology.

**Performance Expectancy**

Performance Expectancy is the degree to which individuals feel using a new technology or system will help them achieve personal or organizational goals more effectively. In the original UTAUT studies applied to ICT, performance expectancy could be divided into categories, or constructs, related to adopting computer hardware and software systems, such as perceived usefulness/extrinsic motivation, job-fit, relative advantage, and outcome expectations. These constructs can be further decomposed into specific, measurable adoption factors. In the case of technology adoption for energy efficient lighting, similar categories can be used. However, categories like job-fit can be redefined as fitness for purpose and combined with perceived usefulness, since goals here can be defined more broadly than simply for employees who are using a technology for one specific job use. “Relative Advantage and Outcome Expectations” can also be combined here, since the advantages that the technology is expected to provided closely match the expected outcomes. Table 3 then lists specific technology acceptance and use factors that can measure various aspects of performance.

**Effort Expectancy**

Effort Expectancy is the degree of ease associated with the use of a new technology or system. Typical construct categories related to this in the ICT literature include perceived ease of use and complexity. For adoption of energy efficient lighting, a single category called ease of operation can be defined that fits the adoption factors found in the literature and listed in Table 3.

**Social Influences**

Social Influences are the degree to which individuals perceive that “important others” believe they should use the new technology or system. For the adoption of ICT systems, “important others” are generally defined as powerful people, such as managers and influential individuals who can exert authority over employees in an organization. For adoption of energy efficient lighting, the definition of authority figures can be much broader, including managers, customers, and other stakeholders who are impacted by the adoption decision. Construct categories in the ICT literature include subjective norms, social factors, and image. For adoption of energy efficient lighting technology, a single category called “Subjective Norms and Image” can be defined that fits with the adoption factors found in the literature and listed in Table 3.

**Facilitating Conditions**

Facilitating Conditions are the degree to which individuals perceive that a technical and organizational infrastructure exists to support the use of the new technology or system. Typical construct categories related to infrastructure in the ICT literature include perceived behavioral control and compatibility. In the technology adoption literature for energy efficient lighting, the same constructs can be defined. Table 3 then lists adoption factors from the literature that fit with these constructs and measure their relevant aspects.

**Most Common Adoption Factors in the Literature**

After defining the construct categories and adoption factors for energy efficient lighting technologies in the previous section, the literature was then examined to determine what was currently known about these adoption factors, and whether some of the factors were considered more common or significant factors for commercial, residential, or industrial users of energy efficient lighting technologies. Table 4 shows a list of the most common adoption factors for each user type. This is based purely upon a review of literature in which researchers referred to specific adoption factors as being more common or significant for various users of these technologies. An explanation is then provided for the reasoning behind these factor assessments. The goal of these assessments is simply to gain a basic understanding of which adoption drivers have been considered the most common or significant for each user type by a subset of experts. Future research will attempt

**Table 4** Technology acceptance and use factors for EE lighting by sector

| Commercial | Residential | Industrial |
|---|---|---|
| Installation cost | Installation cost | Installation cost |
| Energy cost savings | Energy cost savings | Energy cost savings |
| Total cost of ownership | Greenness of product | Payback time |
| Light color | Standards/Compatibility | Light color |
| Start-up speed | Light color | Start-up speed |

to more precisely quantify the exact levels of importance for these and many other adoption factors regarding energy efficient lighting technologies.

An analysis of the most common factors for **commercial users** is provided below. Andrews and Krogmann [9] found that installation cost/upfront implementation cost is the dominant factor driving adoption for commercial users considering energy efficiency lighting technology. The next most significant factor identified was energy cost savings, which was confirmed by a number of other researchers in the commercial lighting sector [7, 39]. Andrews and Krogmann relied on the US DOE's Commercial Building Energy Consumption (CBEC) survey, which is conducted every 4 years [67]. It contains a great deal of information related to energy efficiency, but a limited amount of data related to lighting. So, a number of the factors identified in the literature in Table 3 as important for energy efficient lighting were not specifically analyzed for commercial adopters of energy efficient lighting technology. However, several lines of research mentioned that commercial users, such as those in owner occupied building, considered TCO, as well as issues regarding lighting quality, to be significant adoption factors [8, 37, 43, 47]. Thus, TCO is listed as the third most commonly mentioned factor in the research regarding adoption of energy efficient lighting technologies. TCO can encompass a variety of costs, including initial set up costs, energy costs, and maintenance costs, such as those due to the longer operating lifespan of LED lights. Issues of lighting quality were addressed at various other points in the literature. The most frequently cited issues are solving problems with light color [7, 41] and start up time [38, 45]. So, those qualitative characteristics were rated as the fourth and fifth most commonly mentioned factors that are important for commercial users.

An analysis of the most common factors for **residential users** is provided below. Many studies of factors for energy efficient lighting technology for residential users did not go into as much detailed analysis, particularly on financial and quantitative measures. However, they often did cite qualitative issues affecting consumer intention for adoption. Caird [11] found that installed cost/upfront implementation cost is the main factor of concern for residential users and noted that it is currently perceived as the main disincentive for adopting. The next most frequently discussed adoption factor was energy savings, which, again, consumers perceived skeptically and wondered if the energy savings produced by LEDs was worth the additional cost [14, 36, 66]. Consumers did note, however, that environmental concern was a major factor in considering the adoption of energy efficient lighting technologies, so perceived greenness of the product is listed as the third most commonly mentioned factor [34, 42, 63]. The next most common factor was standards/compatibility. It was noted that LED lighting is perceived as not being widely available for residential use, or that there are concerns it will not be compatible with existing fixtures [7, 12, 13, 47]. Lastly, residential users expressed concern about the light color or quality of energy efficient lighting alternatives [7, 55].

An analysis of the most common factors for **industrial users** is provided below. Anderson and Newell [10] found that industrial users were considerably more responsive to upfront installed cost, rather than energy cost savings when making decisions about the adoption energy efficient lighting technologies. The next most common factor identified was payback time. Industrial users strongly favored short payback times for recovering energy efficiency investments. Many additional factors identified in the literature in Table 3 as significant for energy efficient lighting were not specifically analyzed for industrial adopters of energy efficient lighting technologies. However, various sources in the literature point to similarities in the concerns of commercial and industrial users, since they both need to meet requirements in a business environment, rather than meeting the types of personal preferences often cited by residential users [38, 49]. Therefore, light color [7, 41] and start up time [38, 45], the same qualitative issues as expressed by commercial users, were rated as the fourth and fifth most significant factors for industrial users.

While the studies above present some interesting results, they also need to be examined cautiously. Such literature based assessments often compare studies by researchers using different methods and assumptions, examining industries of different make-ups, and are often conducted in different parts of the world. Clearly this would not offer the ideal framework for readily comparing or robustly analyzing such factors. It simply tries to get the best general consensus from the literature examined in current search. It also offers a baseline, as more data is collected regarding the importance of adoption factors for different user types to compare the similarities or differences in that data to what was previously through a study of the literature.

There are many issues that would need to be addressed to more precisely quantify the relative significance of these adoption factors for commercial, residential, and industrial users. The next section begins the examination of the research needed to more fully quantify the relative differences between the priorities for each of these adoption factors. A variety of methods are anticipated for performing this importance quantification, including expert interviews, surveys, analysis of trade-offs, and dynamic modeling.

## 4 Results

To begin the process of better quantifying the significance of these adoption factors, an important first step is verifying that the variables identified in the literature are seen as significant by experts in the field. A small group of nine experts was contacted to validate the factors presented in Table 3 and determine which ones looked most promising to focus on in further studies. The group consisted of nine experts, who were drawn from a variety of backgrounds, including: Electrical Engineering (2); Mechanical Engineering (2); Lighting Design/Manufacturing (2); Lighting Installation (1); and Architecture (2). All experts were familiar with the application of lighting technologies in commercial, residential, and industrial settings, although a number of them specialized primarily in one or another of these sectors. Overall, there were a roughly equal number of experts who specialized in areas related to each sector.

The experts began with the start concepts derived from the literature, but they were free to add factors if they felt additional concepts were important or to indicate if they felt any of the factors were inappropriate or not significant. One additional factor, Programmability/Energy Management, was identified through this process, bringing the total number of factors examined to 22. To rapidly gather input from this group of experts, which was composed of people from many different backgrounds, a charrette technique was used to allow them to quickly validate and prioritize variables through the use of a voting process [68]. Each expert was allowed to cast a total of five votes, assigning no more than one vote to a single factor. This permitted the experts to identify the set of five factors they considered to be most significant, without worrying about exactly how the factors ranked in terms of relative importance. All votes were then tallied to reveal the consensus regarding the factors that the most experts considered significant. These results are presented below.

A number of interesting results are evident from the expert judgment data. First, there are some similarities with results from Table 4. The largest number of votes in all sectors went to Installation Costs and the second largest number to Energy Cost Savings. However, in the Industrial sector, there was a tie for second place, between both Energy Cost Savings and Payback Time. Because of the possibility of ties, the third, fourth, and fifth highest choices become more complicated and are not always easy to spot on a tabular data format. Therefore, Fig. 2 below attempts to summarize the data in a more graphical format where the highest choices for each sector stand out a little more prominently. For example, the third highest choice for the Commercial sector is TCO, which is consistent with Table 4. For Residential sector, however, it includes Greeness of Product, which is consistent with Table 4, but it is also in a three-way tie for third place with Light Color and Standards/Compatibility. For the Industrial sector, there is also a three-way tie for third place between TCO, Standards/Compatibility, and Maintenance Costs. This is somewhat different that Light Color and Start-up Speed, which were found to be the third and fourth highest factors on Table 4 for the Industrial sector. However, those factors are listed as one several different choices rates as the fourth highest for this sector on Table 5. A number of other similarities and differences can be observed on Fig. 5 regarding the shape of the data patterns between the various industries.

The goal of the expert judgment data contained in Table 5 and summarized in Fig. 2 was not to establish an exact or definitive measurement of the rankings of adoption factors, it does provide a general picture of the significance of different

**Table 5** Expert judgment—technology acceptance and use factors for EE lighting by sector

| Commercial | Count | Residential | Count | Industrial | Count |
|---|---|---|---|---|---|
| Installation cost | 6 | Installation cost | 5 | Installation cost | 6 |
| Energy cost savings | 5 | Energy cost savings | 4 | Energy cost savings | 5 |
| Total cost of ownership | 4 | Total cost of ownership | 2 | Total cost of ownership | 3 |
| Light color | 3 | Light color | 3 | Light color | 2 |
| Standards/ Compatibility | 3 | Standards/ Compatibility | 3 | Standards/ Compatibility | 3 |
| Start-up speed | 3 | Start-up speed | 2 | Start-up SPEED | 2 |
| Maintenance cost | 2 | Maintenance cost | 2 | Maintenance cost | 3 |
| Ease of maintenance | 2 | Ease of maintenance | 2 | Ease of maintenance | 2 |
| Payback time | 2 | Payback time | 2 | Payback time | 5 |
| Incentives or promotional policies | 2 | Incentives or promotional policies | 2 | Incentives or promotional policies | 2 |
| Taxes or tariffs | 2 | Taxes or tariffs | 2 | Taxes or tariffs | 2 |
| Brightness | 2 | Brightness | 2 | Brightness | 2 |
| Importance of recyclability | 2 | Importance of recyclability | 2 | Importance of recyclability | 1 |
| Programmability/ Energy management | 2 | Programmability/ Energy management | 1 | Programmability/ Energy management | 2 |
| Ease of use | 1 | Ease of use | 2 | Ease of use | 1 |
| Flicker | 1 | Flicker | 2 | Flicker | 1 |
| Public environmental consciousness | 1 | Public environmental consciousness | 1 | Public environmental consciousness | 1 |
| Greenness of product | 1 | Greenness of product | 3 | Greenness of product | 1 |
| Energy prices | 1 | Energy prices | 1 | Energy prices | 1 |
| Recycling infrastructure | 0 | Recycling infrastructure | 0 | Recycling infrastructure | 0 |
| Ease of recyclability | 0 | Ease of recyclability | 1 | Ease of recyclability | 0 |
| Social significance of adoption | 0 | Social significance of adoption | 1 | Social significance of adoption | 0 |

factors in each of the sectors and shows some results that both support and diverge from the results in Table 4. Although some factors, such as Recycling Infrastructure received no votes, and Ease of Recyclability received only one, that does not necessarily mean those factors are not important or should be excluded from future studies. Importance of Recycling was listed as a significant factor in all sectors. The expert panel was provided an opportunity to say if they believed any factors should be excluded, and none were identified. However, one way to interpret factors with a low number of votes is to say that those aspects of recyclability were not clearly top of mind for many experts. Therefore, they may not be listed as start concepts on future measurement instrument, and there may instead be clarifying questions about recyclability asking if the current factors adequately address the issues related to recyclability that respondents consider important. If they do not, additional terms can be proposed which may better express

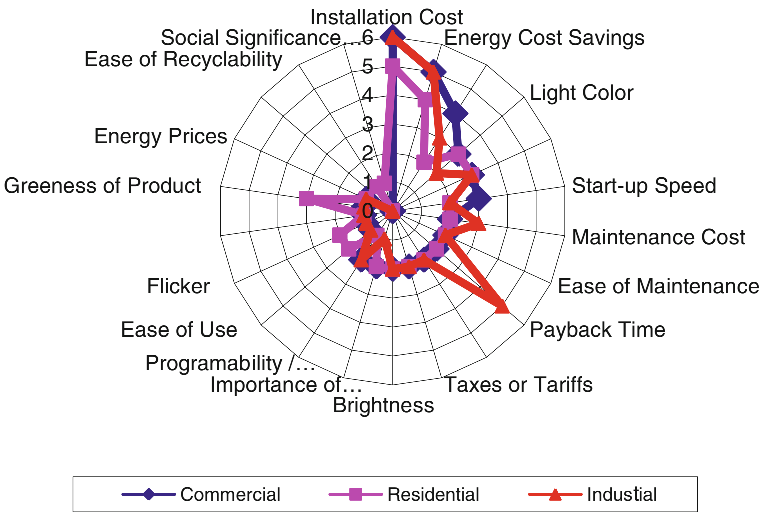


**Fig. 5** Polar chart—technology acceptance and use factors for EE lighting by sector

concerns related to these issues. The next step in this research will then be to create a survey to more precisely measure the relative importance of the various factor affecting the acceptance and use of technologies for energy efficient lighting.

## 5 Conclusions

This research used several methods to determine what is currently known about the factors that are thought to most commonly influence adoption behavior for energy efficient lighting technologies in the commercial, residential, and industrial sectors. Literature was reviewed regarding the adoption of energy efficient lighting technology, and the most commonly used terms were identified and sorted according to the UTAUT framework. LED lighting was a specific focus among the energy efficient lighting technologies, as a number of studies identified it as a promising new lighting technology, which offers many advantages in terms of energy savings and long operating life of the product.

An initial review analyzed several groups of studies from the commercial, residential, and industrial sectors to determine if there was consensus on some of the factors most common to each industry. Installed Cost and Energy Cost Savings were found to be the factors most commonly considered significant in motivating adoption in all three sectors. Other factors varied in each sector, though the Commercial and Industrial sectors were believed to be the most similar. It was difficult to reach a clear consensus on the top five factors in each sector, so a group of experts was contacted for an exploratory study to validate and prioritize the wider set of factors identified in the literature, as well as determine if they felt specific factors should be added or removed. This research also found that Installed Cost and Energy Cost Savings were the two most common factors for all three sectors. However, among the third, fourth, and fifth level choices, there were many ties for the most common factors. While this did not establish precise rankings for these factors, it provided some initial insights into the complex set of factors influencing each sector. It is valuable to see that there may be a number of factors which are significant at each level. The next step in this research will be to create data collection instruments to more precisely quantify the relatively importance of different factors in each of these industries.

Behavioral theories of technology adoption, such as UTAUT, were discussed in this paper to explain how stakeholder expectation and buy-in could influence the acceptance and use of new technologies. This was seen as being particularly important for the adoption of energy efficiency technologies, because these technologies tend to be very dependent on continued acceptance and involvement by users in order to realize the full benefits they can deliver. The literature reviewed in this study identified adoption factors associated with each of the four key construct categories of UTAUT and explained how these constructs could be applied to understanding energy efficient lighting technologies. However, customization of these constructs would be necessary to operationalize them for measuring specific aspects of these technologies in future research.

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# How Can Small and Medium Enterprises Maintain a Balance of Research and Development?

**Karina Hershberg, John Elliot, Sajeda Tamimi and Tugrul Daim**

**Abstract** The objective of this project is to gain a better understanding of how small and medium sized enterprises (SMEs) balance research and development (R&D) activities. We explore modern R&D tools and methodologies through literature research. These tools and methodologies are then aligned with "External Variables and Internal Conditions" as identified by Keizer et al. and a framework is created [1]. This framework is applied to a case study. The case study examines HECO, the Hawaiian Electric company, representing a small enterprise. The results of this analysis show that the proposed framework for understanding SME R&D programs is viable.

## 1 Introduction

Small and Medium Enterprises (SMEs) have played and continue to play significant roles in the growth, development and industrialization of many economies around the world. SMEs have been driving the U.S. economy in the last few decades, by providing jobs for over half of the nation's private workforce. One article notes the following:

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> Office of Advocacy funded data and research shows that small businesses represent 99.7 % of all firms, they create more than half of the private non-farm gross domestic product, and they create 60–80 % of the net new jobs [2].

Not only did industry funding for R&D grow rapidly in recent decades, but so did the numbers of R&D alliances, mergers and acquisitions, and patent licenses. Moreover, the share of R&D conducted by SMEs and business funding for university research increased significantly [3].

This suggests that SMEs have adopted "new models" of knowledge creation, management, and sharing that supplement more strategically oriented internal R&D activities with greater use of externally acquired technology.

We have to aligned these new models and tools with variables that can be considered as "possible predictors of innovation efforts" as defined by Keizer et al. [1]. Keizer's paper conducted in depth research of the different variables impacting R&D in SME's. They concluded that the variables could be classified as *external variables* and *internal conditions*. External variables refer to opportunities SME can take advantage of in regards to its environment, while internal conditions refers to the characteristics and policies of SMEs [1].

## 1.1 Objective of the Study

This report intends to explore the models and key business survival strategies, which have worked for SMEs. These strategies are listed below.

- Partnerships with Universities and other companies [4].
- Global teams [5].
- Open innovation [6].
- Licensing, Patents and trade secrets [4].
- Speed to Market [4].
- Corporate Entrepreneurship [7].
- Collaboration tools [5].
- Improved designs and processes [8].
- Platform based development [9].

By applying these variables and tools to the case study, we hope this report will lead to a better understanding of the way in which SMEs conduct research and development activities.

## 1.2 Challenges and Opportunities

The problems and challenges that SMEs contend with are enormous. For example, they have to deal with limited resources, inability to spread risk over a portfolio of new products, too many partners, problems in funding longer-term R&D, and marketing issues [10]. Moreover, the unfair competition and government policy inconsistencies and bureaucracy increases these challenges and make it difficult for SMEs to innovate [11].

However, it is important to note that many SMEs are able to overcome these challenges. This should provide a basis for optimism that there is an opportunity and a way out.

Due to their relatively small/young environment, they enjoy a number of behavioral advantages over their larger counterparts. They have an interactive management style which makes internal communication more efficient so they can respond rapidly to external threats and opportunities. SMEs can make decisions and implement them faster. They can react more quickly to input from customers or challenges from competitors, and evolve their business models more rapidly [10].

Their smaller size makes smaller markets attractive to SMEs. This advantage allows SMEs to exploit new trends sooner when entry costs are still quite low. Moreover their focus lets them execute very effectively against larger, diversified firms. It was also found that SMEs attract more entrepreneurial R&D employees. All of these advantages lead to their strong licensing ability [12].

## 2 Background

A lot of research has been conducted recently to find out which factors contribute to innovation efforts by SMEs. These studies revealed that activities directed to innovation correlate with a number of variables. These variables were classified by Keizer et al. as **External Variables and Internal Conditions.** External variables refer to opportunities SMEs can seize from the environment. Internal variables refer to characteristics and policies of an SME [1].

### *2.1 External Variables*

#### 2.1.1 Collaborations with Other Firms

SMEs can be integrated into the supply chains of large companies, using a technical- and business-skills mentoring approaches such as: partnerships with other firms, open innovation, and licensing.

#### 2.1.2 Linkages with Knowledge Centers

This tool helps make SME's more competitive through consultation with universities, researchers, and technology centers.

#### 2.1.3 Utilizing Financial Resources or Support Regulations

There are number of financial programs for SMEs, some of them are governmental funds, and some provide a number of different resources and opportunities for finding SMEs funding.

### 2.2 Internal Conditions

#### 2.2.1 Strategy

There are different R&D strategies for SMEs, which allow them to compete with larger firms, like speed to market. SMEs take decisions faster and implement them more rapidly. They can react more quickly to input from customers or challenges from competitors, and evolve their business models more rapidly [12].

#### 2.2.2 Structure

Efficient internal communication and interactive management style often represent the structure of SMEs. Their smaller size allows them to attract smaller markets. Their focus and business specialization lets them execute very effectively against larger, diversified firms [12].

#### 2.2.3 Technology Policy

Through patents, Intellectual Properties, and Licensing, SMEs can be integrated into the supply chains of the large companies. Moreover, these policies are considered survival methodologies that allow SMEs to become a key player in the market.

#### 2.2.4 Level of Education

Presence of qualified engineers and the number of PhDs and Masters researchers plays a key role in the development of the SMEs and the effectiveness of their research. Also, the degree of education of the founder/manager is an important factor in the progress and sustainability of the company [1].

#### 2.2.5 Investments in R&D

Investment Policy is critical for SMEs. Unlike large firms, R&D investment is considered risky and controlled by many factors, such as: company's age and size, available funds, priority of the project, and relativity of the project to their main goal.

#### 2.2.6 Geographical Location

This variable refers to the influence of location (Rural or urban location) on their collaboration with other firms, universities, and research labs, etc. Of course this depends on the enterprise's industry. The company should also explore the potential advantages and disadvantages of "Virtual and Global teams" for maximizing the impact of R&D investment.

We can take these external variables and internal conditions use them as a framework to help analyze our case study. For the case study we will look for evidence of this framework and identify how the SMEs are impacted.

## 3 Case Study

The goal of the following case study is to show how small and medium sized companies handle research, development and deployment of new and innovative products or concepts.

### *3.1 Case: Hawaiian Electric Company*

#### 3.1.1 Introduction

For the small company case study, the selected organization is actually a subset within a much larger company. Due to the nature of their work and the structure of the industry, this group functions very similarly to a small company and therefore met the criteria of the case study. The selected small company is the Renewable Energy Division that is part of one of the main Hawaiian utilities, Hawaiian Electric Company (HECO). Although the parent utility is a large organization, utilities have historically not functioned as R&D institutions. Therefore even though the renewable energy division is technically part of HECO, in many ways it runs like a small, semi-independent group. This includes the ways that they find sources of funding, develop industry and academia collaborations, and their portfolio development strategies. The interface with the larger utility mostly occurs once the technology or concept is ready for deployment. As such, the renewable energy division fills an RD&D role for the utility- research, development and deployment.

The source of information for the HECO Renewable Energy Case Study was interviews with the Director of the Renewable Energy Division. Research for the case study was conducted through a written questionnaire and phone interview. The study focused on the group's strategies for funding, developing collaborative relationships with external organizations and portfolio development. Many of the challenges, as well as the opportunities, found in the literature research are demonstrated in this case study.

### 3.1.2 Background

The utility industry does not historically have a reputation for being leaders in research and development activities. Due to strict regulations around system reliability, utilities are cautious to take on risk and make changes to the system. But as both the government and the public begin to demand more focus on fossil fuel alternatives and energy efficiency, the utilities are entering into a world that they have historically not participated in—research, development and deployment. HECO has been an active and leading player in the push towards upgrading and innovating both generation sources and distribution methods of the Hawaiian electric grid. The HECO Renewable Energy Division (referred to from here forward simply as "HECO") provides an informative example of how utilities can begin to successful enter and participate in R&D activities.

### 3.1.3 Collaboration with Other Firms, Universities and Knowledge Centers

Successful collaborations have been one of the biggest factors in HECO's success. There are two benefits to the collaboration of R&D for utilities. The first is the more obvious one, which is the sharing of resources and ideas that can lead to stronger innovative efforts than either side could produce alone. This is especially key in the area of energy because the end users, the utilities, often are not doing their own development. This can result in both a stagnation of progress, as well as a disconnect between the developer and the user. But a collaboration between the utility, industry and academia helps tie the research abilities of academia with the development resources of industry with the deployment potential and end user needs of the utility. The added advantage of partnering with academia is that research for real world applications helps develop and train a future workforce already knowledgeable on the issues of the industry.

The other benefit of collaboration relates back to the structure of the funding resources. Most of HECO's funding come from external sources that require strategic and creative approaches which necessitate partnerships with academia, research facilities and industry. Collaboration is often the key to winning grants and is often one of the intended outcomes of such programs. While researching the effect of government funded programs in Hungary, Inzelt comments "Throughout the world, policy programmes tend to call for collaboration and integration, and R&D and innovation policy programmes are important coordinating forces in the field of funded research and of supported innovation activities" [13]. Although government funded grants are sometimes intended to encourage these collaboration, the system is often so complicated that only experienced teams can successfully find partners, apply for, win the grants and then properly spend the money in qualified projects. HECO's success in understanding this system and the type of relationships that are needed has been crucial in helping them become a successful and innovative player in the renewable energy field.

### 3.1.4 Utilizing Financial Resources or Support Regulations

As mentioned in the previous section, funding is a big issue for HECO. Since utilities historically haven't functioned as R&D organizations, they are not set up to support large research and development programs. This means that a R&D group like the Renewable Energy Group is often responsible for securing their own funding resources. But this is not a unique problem and finding funding is an issue most SMEs groups grapple with. The quest for funding can often be difficult and introduces additional risk to the program. The ability to successfully navigate the funding avenues can be the determining factor between small companies that have successful R&D programs and ones that do not.

In the case of HECO, much of their funding comes from grants but this does not come without its own set of challenges. The literature found that two of the challenges SMEs face are "problems in funding longer-term R&D" and "government policy inconsistencies and bureaucracy" [10, 11]. Both of these issues are clearly demonstrated in US federal grant programs for energy research, which often are short term. This makes it very difficult for groups to plan far in advance. This is a problem for most small R&D programs, but it is especially challenging for groups in the utility industry, which has historically been slow to change and requires significant testing before any modifications to the system can be made.

In addition to the constraints of the funding timelines, there seems to be some other disconnects between the funding sources and the funded programs. While researching factors impacting innovative research, Keizer et al. found a study concluding "only a very small number of SMEs seeking financial resources failed to succeed" [1]. This is perhaps a misleading statement because it does not necessarily account for all the small R&D groups that would like to apply for funding but have not successfully figured out a way to even enter the system. HECO has observed two main disconnects between the funding sources and the hopeful funding recipients. The first disconnect is in academia. The educational research groups are often able to get the funds, but they don't necessarily know the needs of the industry well enough to successfully use them. The second disconnect is industry, which knows what the research needs are but doesn't understand how to get the money or how to work within the stipulations of the grant. A successful R&D groups needs to understand three key areas- how to find the funds, how to apply for the funds and how to use the funds. This need for collaborative efforts and a broad range of skills sets is one of the reasons the previously discussed partnerships and collaborative efforts are so key in developing a successful program.

### 3.1.5 Strategy

HECO's strategy for project selection is a strong example of the impact of external variables. The main variables that effect HECOs program portfolio are need, funding, regulatory factors and public policy. Industry culture is another factor since utilities are often risk adverse and more reactionary than proactive when it comes to change. The issue of public policy is a complicated one because it is influenced by its own set of external factors and is constantly changing. But when partnered with an accepted roadmap and aligned with the larger goals of the organization, it is possible to successfully move forward with project development and deployment.

The HECO Renewable Division has a roadmap that helps them determine which projects to focus on. In general their goal is "to sustainably and reliably bring on more renewable to the islands and advance the state of the industry" Their platforms look at new technology, improvement of the efficiency of existing technology and data collection to better model and develop the overall system.

### 3.1.6 Level of Education

In the case of HECO, the internal variable defined in the literature as "Level of Education" can perhaps be more broadly defined as caliber of employee. A well known factor in successful project management is that great programs attract great employees. Since the energy industry has not historically participated in much innovation, the push for exploration of new ways to produce, distribute and use energy has created an exciting environment that is helping attract talented people to the field. Since HECO has become one the leaders for renewable energy research among the US utilities, it has helped them to attract capable and motivated employees who are both excited and challenged by the innovative projects they are working on. Director Dora Nakafuji commented, "This is an exciting time to be working in the energy industry".

### 3.1.7 Challenges

Most of the SME challenges that HECO faces tie back to funding in some way. From the list provided in Sect. 1.3 of this paper, the SME challenges that apply to HECO are Limited Resources, Problems in Funding Longer-Term R&D and finally, Government Policy Inconsistencies and Bureaucracy. Although the government grant programs help initiate the formation of partnerships, the short life cycle of the grants are ironically counter-productive both in the collaborative relationships and the level of R&D that can be supported. A solid partnership can take 10, or even 20 years, to solidify but the funding programs are often five years or less. Therefore the issue of limited resources and government inconsistencies end up causing problems with funding longer term R&D programs.

Despite these challenges, HECO has been unusually successful in finding ways around them and could serve as a valuable learning tool for other US utilities hoping to advance their involvement with renewable energy and energy efficiency R&D programs.

### 3.1.8 Opportunities

Although being an SME has its challenges, there are also advantages to being a small organization and, when used properly, can provide unique opportunities. Of the advantages listed in Sect. 1.3, the three that are well demonstrated in the HECO case study are Rapid Response, Focus and Speed.

Focus is perhaps as much a product of the industry, as HECO's size. Their focus is on renewable energy technologies, improved resource forecasting and integration, improved distribution and allocation and smarter systems on all levels. This is obviously an extensive list and not necessarily a narrow focus, but since the regulatory forces on utilities have specific requirements around when and how changes can be implemented, HECO has at least some direction on where to focus their efforts. They work off of a living roadmap that focuses on five platforms of need.

One of HECO's biggest advantages is their size. In this case, although the parent utility is large compared to the Renewable Energy Division, it is in fact still considered a smaller utility. This has allowed them to be more nimble and adopt changes more easily than some of their larger sister utilities in other states. The flip side is that their victories don't always have as much widespread impact on the industry. In the future, HECO would like to continue using their small size as a chance to be a test bed for new solutions but also become an example of programs that can then be rolled out to larger utilities around the country.

### 3.1.9 Conclusions

HECO proved to be an interesting case study but not only because of their status as a small R&D organization. Their understanding of the R&D funding labyrinth in the renewable energy industry, as well as development and deployment in the utility industry, provided valuable insight into the weakness of the current system and ways that support of R&D programs could be improved in the future. The end conclusion was that the money is there, the needs are there and the brainpower is there for renewable energy research, development and deployment programs. But the hurdle that is left is figuring out a way to better connect the three so that these programs can really start to flourish.

## 4 Conclusion

The results of our research show that there are many variables involved in the development and long term survival of a successful SME R&D program. The variables, challenges and opportunities identified in the literature were easily correlated to the real world example, indicating that our proposed framework for analyzing SME R&D efforts is viable. Although both of the case study dealt with companies that have been successful in managing R&D efforts, the ongoing struggles they face highlight the challenges than accompany the opportunities of managing a small or medium sized R&D program. But if done properly, it can produce a rewarding, exciting and successful program.

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# A Framework for Green/Eco-Innovation Through Use of a Novel Measure: E/R

**Liliya Hogaboam, Alptekin Durmusoglu, Turkay Dereli and Tugrul Daim**

**Abstract** Eco-innovation has been a recent idea used to describe development of products, services and processes that contribute to sustainable development (SD) through commercial application of knowledge considering ecological facts. This chapter introduces a green/eco-innovation framework incorporating the uncertainties and acquisitions together. A measure is used to indicate the ratio between "possible risks" and "values added". This measure is named as "E/R" ratio, where E represents "eco-innovative acquisitions provided by the proposed novelty" and R denotes the "risks which arise as the consequence of novelty". A simple evaluation structure has been developed to calculate the value of E/R ratio for a certain novelty. Proposed framework is tested through the case of green buildings providing an insight into the risks associated with them.

## 1 Introduction

Water scarcity has emerged as one of the most pressing problems in the twenty first century [1]. It is estimated that 2.7 billion people will face water scarcity by 2025 [2] and several wars could explode. It is obvious that, for today's highly

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populated habitat, "scarcity problem" (not just water scarcity) signifies a much more hazardous situation for the world. Scarcity has been a problem which threatens today's community with a higher potential to affect the living standards of future generation. "Scarcity" term, points out to the inequality of the desires/needs of human and the resources available to match them. The solution to the scarcity problem, which human-being is engaged with, is supposed to be found within equilibrium where the needs are satisfied without abolishing the resources. There have been several studies which are focused on finding such an equilibrium point. Objective of these efforts has been to analyze scarcity problem and its link to environmental/ecological change and to identify options for a more sustainable planet. Therefore, it is claimed that, the concept of sustainability- has emerged as the consequence of equilibrium search to scarcity problem. Sustainability concept dates back to studies performed by Malthus [3] on population growth in the late eighteenth century. Thomas Malthus, who published an essay on the "Principle of Population" in 1798, warns society about the fact that population increases exponentially and food production increases only incrementally.

Approximately 200 years later, an official definition for sustainability was declared by the Brundtland Commission Report in 1987 [4]. It was: "meeting the needs of the present generation without compromising the ability of future generations to meet their needs". After the summit, a series of subsequent meetings were held and "Agenda 21" report was published. The report was a comprehensive global strategy towards sustainable development. It is worth mentioning that almost all parties were impressed with Brundtland's definition of sustainability. However, the phrases used in the definition were not clear and these phrases have introduced discussions about the real meaning of sustainability. What was the word "need" referring to? Was the definition indicating lowering of living standards and luxury? It should be expressed that these questions still have value and they are still discussed.

After a five year gap, Rio Earth Summit had been held in Brazil. 172 governments participated, with 108 sending their heads of state or government [5]. As an important outcome of the summit, some essential documents for sustainable management/development have been discussed and declared to the public. At the same summit, "*C*ommission for *S*ustainable *D*evelopment" (CSD) has been founded by the United Nations General Assembly. CSD was also employed with follow-up implementations regarding the Rio Summit.

Millennium Summit has been another milestone for sustainable development. Summit's final declaration was signed by 189 countries. International community promised to apply a specific agenda to reduce global poverty and starvation problem. In parallel to these milestones, the concept of sustainable development (SD) has become a leading goal of policy makers and scientific researchers [6]. It has been a widely acknowledged concept used by organizations representing all scales of governance: local, regional, national and international [7]. On the other hand, philosophical arguments have been issued in scientific journals, to develop a deeper understanding of the real meaning of sustainability. Sustainability has been regarded as both an important but unfocused concept like "liberty" or "justice" [8, 9] and as a feel-good buzzword with little meaning or substance [10, 11]. The views on sustainability were not surprising since the concept was comparatively young, complex and abstract [12]. As a consequence of these debates, scientists have all agreed that "sustainability" is a multidimensional concept and it encompasses economic, social, and ecological perspectives of conservation and change. Therefore, several stakeholders and scientists from different disciplines, including engineers, have been all involved in sustainability and sustainable development.

## 2 Literature Review

Relationship between resources and the demand for these resources has been subject of economics science. Economics as being 'the study of the most favorable conditions for giving society the greatest amount of useful products with the least waste of human energy' [13] has its roots on the reality of limited resources against the unlimited wants and needs. However, the "sustainability" has been a multidimensional concept and the role of engineers in sustainable development cannot be disregarded. Engineers have been stakeholders of the scarcity problem and sustainability since they are responsible to design machines, tools, devices, processes, systems and employ materials to these designs. They are the providers of the mechanisms for the transfer of technical skills and comprehensive planning techniques to implement "sustainable development" at an individual, corporate, and institutional levels in developing and developed countries. Engineers are involved in sustainability from all aspects such as; resource use, from resource extraction through to technology/product/process design, manufacture, operation and management of wasted resources and products. For an engineer, creating sustainable systems involves making engineering and New Product Development (NPD) decisions based on multiple dimensions: technological, ecological, economical, and socio-cultural, including ethical [14]. Furthermore, creating sustainable systems involves making use of an "integrated systems approach" (holistic approach) which considers all stakeholders and the possible consequences on the environment once attempting to solve problems. They should focus on an overall synchronized solution rather than solely on the technology aspects, and solving one problem at the expense of another.

It is certain that much more items/tasks could be listed to define the role of engineering in sustainable development. However there is a certain need for a well-defined guideline describing these roles. Even though the role of engineering for sustainable development has been discussed in many platforms, as well in this chapter, there has not been a well-defined guideline describing these roles. Canadian Council of Professional Engineers (CCPE) has been one of the institutes which proposed a "well intentioned guide" for the key roles of engineers. CCPE declared a report [15, 16] stating that "professional engineers have an obligation to be mindful of the effect that their decisions will have on the environment and the well-being of society" and "shall hold paramount the safety, health and welfare of the public, and the protection of the environment". One other effort has been the organization of a high-level workshop on centralization of engineering for the sustainable development policy, research and delivery, by Royal Academy of Engineers and Defra [17].

Technology is one of the most important ways for human being to interact with their environment. People use technologies for various purposes such as to extract natural resources, to modify them for human purposes and to adapt our man-made living space [18]. It is required to be conscious and thoughtful in employment of technology in order to cover distance towards sustainability. Since there is a need for a certain awareness to use technologies, engineer's role in developing technology is very important to keep the sustainability.

Even though it is important to develop sustainable products, processes and systems, it would not make sense to do so for the entrepreneurs and customers, if they cannot be commercialized. Therefore it is more rewarding to develop "sustainable and worth-trying" products for customers. "Eco-innovation" is the right term defining the development of sustainable products which has certain commercial value. Sustainable innovation/eco-innovation is an emerging and fundamental force for change in business and society [19]. James [20] defines: "eco-innovation is one of several approaches towards sustainable product design, which aims to provide customer and business value whilst significantly decreasing environmental impact". These two objectives can be obtained through design of products and processes which maximize resource and energy efficiency, minimize (or preferably eliminate) waste and reduced harm to the environment [21]. However, achieving these objectives may not be as easy as it is considered. A framework defining the path through eco-innovation in a stepwise manner is expected to be beneficial for eco-innovation.

Although several definitions, objectives and techniques have been provided for "eco-innovation", the effort to present a general framework for "eco-innovation" has been limited. One of the earliest efforts for a design of such a framework has been performed by Brügeman [22]. She considered Roozenburg and Eekels's [23] product innovation model (PIM) and took "possible merits of sustainable function of innovation" into account to present an eco-innovation framework for service design. She added two steps to Roozenburg's PIM. The model was based on collaboration of possible utilities which can be obtained considering *E*co-efficient *S*ervices (ES). The model initialized with exploration phase where decisions on establishment of a right collaboration are made (such as determination of partners and the divided responsibilities). In the last part of the model, an evaluation phase is performed through the use of indicators of "Design for Eco-Efficient Services" (DES). DES indicators measure the possible environmental improvements which can be turned out by the novel service. Hallenga-Brick and Brezet [24] considered the weaknesses of DES model developed by Brügeman's [22] and proposed a novel framework (Sustainable Innovation Design Diamond Model) to support design of efficient sustainable innovation strategies. They have determined six fundamental diamonds which describe milestones of a design project. One well-structured framework for eco-innovation (interchangeable with "Green Engineering") was published by Anastas and Zimmerman [25]. They have announced 12 Principles for Green Engineering, which has been a design protocol for engineers to utilize in moving towards sustainability. The principles listed by Anastas and Zimmerman [25] have been used as a framework by designers to consider them as fundamental factors at the earliest stages of design.

The application of principles across scales and across disciplines has been documented with case studies from a variety of sectors [26, 27]. Fundamental approaches and instructions in moving towards sustainability have been common for different industries. These implementations also provided guidelines for improving sustainability through the design and development of technologies. Rocha et al. [28] have also proposed a sustainable development management framework which integrates seven key factors: stake-holders, resources, leadership, processes, values, objectives and results. The proposed framework enables the introduction of sustainable development principles in each of these seven factors. It also takes, the interrelationship and trade-offs between them at the macro level, into account. This allows managing the overall strategy according to a whole system perspective that considers short- and long-term impacts. Recently, Flores et al. [29] proposed a framework to be used as a reference guideline for organizations to define a roadmap, specific actions and projects to achieve sustainable innovation, integrating four key enablers: mass customization, sustainable development, value network and complete product and service life cycle. Mass customization (MC) targets the identification and compliance with specific needs and requirements of customers in order to achieve customer-driven design. At the same time, the sustainable development (SD) paradigm is taken into consideration, where, for any new product or service companies analyze the benefits, risks and impacts of not only economic factors, but also social and environmental implications. The third enabler is linked to the value network (VN), where innovations happen owing to the active collaboration and distributed knowledge of partners inside and outside the company. Finally, the fourth and last considers the complete product and service life cycle (PSLC), where the above mentioned three sustainable elements are identified and analyzed in each single business process.

## 3 Methodology

There have been several efforts to measure eco-innovation. Some of these measures are developed to draw a macro level figure for eco-innovation (surveys, patent analysis etc.) however, some other measures are developed to create a benchmark for eco-innovators to measure how much they reduce environmental burden (ex: [30]). However there has been a serious gap in development of a measure considering the risks due to new product development.

As indicated by James [20], there are two main objectives of eco-innovation: (i) providing customer and business value; (ii) decreasing environmental impact. It is important to consider both of these objectives and follow a systematic path during the New Product Development (NPD) process. However, risks arising from NPD should not be ignored. Because of NPD's inherent features, NPD decisions inevitably encounter a considerable amount of uncertainties which may result in negative consequences of the targeted performance [31, 32]. Therefore, it is apparent that it is important to consider "possible risks" and "values added" by eco-innovation prior to initialization of NPD process.

A measure or ratio can be defined to indicate the relationship between "possible risks" and "values added". Therefore, a ratio is proposed in this work. This ratio has also been employed in the proposed framework. This ratio is named as "E/R" ratio, where E represents "eco-innovative acquisitions provided by the proposed novelty" and R denotes the "risks which arise as the consequence of novelty". Possible acquisitions and risks of eco-innovation need to be defined first to prepare E/R ratio. Seven major eco-efficiency elements defined by World Business Council for Sustainable Development (WBCSD) are used to describe the benefits of novel eco-friendly products or processes [33]. Chin et al. [34] recent study has been considered to outline the risks of NPD since they have scanned literature and prepared a well-structured risk map for NPD.

A "7 × 8 matrix" is build up and presented in Fig. 1, where rows indicate the "acquisitions provided by the proposed novelty" (E) and columns indicating "risks which arise as the consequence of novelty" (R).

A simple evaluation structure has been developed to the calculate value of E/R ratio for a certain novelty. If the novelty added to product has ecological value, it should satisfy at least one of the items listed in rows (E), however the indicated novelty can also create the risks given in columns (R). Then the E/R value of the novelty is:

| ***E*** \ ***R*** | CPD | SEP | RDC | PES | CPP | SES | SPP | PRC |
|---|---|---|---|---|---|---|---|---|
| **$E_1$**: Reduce the material intensity of goods and services (material reduction). | | | | | | | | |
| **$E_2$**: Reduce the energy intensity of goods and services (energy reduction). | | | | | | | | |
| **$E_3$**: Reduce the dispersion of any toxic materials (toxicity reduction). | | | | | | | | |
| **$E_4$**: Enhance the recyclability of materials (material retrieval). | | | | | | | | |
| **$E_5$**: Maximize the sustainable use of renewable resources (resource sustainable). | | | | | | | | |
| **$E_6$**: Extend the durability of products (product durability). | | | | | | | | |
| **$E_7$:** Increase the service intensity of goods and services (product service). | | | | | | | | |

**Fig. 1** E/R Evaluation Matrix

$$E/R = \frac{\sum_{i=1}^{i=7} \#\ \text{of risk factors provided by the proposed novelty by acquisition}\ E_i}{7}$$

As an exemplification, think of a novel eco-innovative product proposal adding value to an existing one by reducing material intensity of goods. However, in case of realization, it will be very similar to an existing product in the market (SEP) and company's potential to articulate successful R&D activities on this novelty is very difficult (RDC). At the same time, company requires many new machines and equipment to realize production. However the other risks are not expected to occur. At this time, we have three risks and one "eco-innovative single acquisition provided by the proposed novelty", then E/R value for E1 is, 1/3 and we need to calculate the other acquisitions in the same manner and add them up.

Innovation is typically an iterative and interactive process [35]. Like the other iterative processes, innovation requires a base product/process or service to iterate. Majority of patents are related to improvements to existing patented inventions and they form a base for innovation processes. NPD as being a sub process of innovation [36] can utilize patents to search for gaps in the relevant technologies [37] and thereby patents are known to be one very useful source for stimulating innovations.

In this chapter, a novel "*eco-innovative-new product development*" framework has been introduced to support companies in their decisions to add/remove a novelty of an existing product. The proposed framework is initialized with the selection of a significant patent to focus on/iterate. Subsequently, the selected patent is evaluated using "E/R ratio" which is also introduced in this work (previous section). The patented technology/product or service is then could be improved using several "creativity management" tools like "Theory of Inventive Problem Solving" (TRIZ), "Quality Function Deployment" (QFD) and "Cased Based Reasoning" (CBR). The possible improvements are re-evaluated using "E/R ratio" and then a new value of "E/R ratio" is benchmarked with the patented one. A final decision is made upon this benchmarking. Figure 2 illustrates the steps of the proposed framework for developing eco-innovative product. The remainder of this section describes steps in detail.

### *3.1 Step 1: Selection of a Significant Patent*

Patents are seen as a rich, but often insufficiently utilized source of technical information. Much effort have been undertaken to popularize and promote the use of patent information. A central element of these activities has been the launch of freely-accessible databases on the Internet [38, 39]. Although it is possible to access all granted patents, it is still difficult for a company to find a significant patent through millions of patent documents. Patent Alert System (PAS) recently developed by Dereli and Durmuşoğlu [40] presents a practical solution for


**Fig. 2** Steps of the proposed framework

selection problem. PAS is an extended mark-up language (XML) based expert-system which watches the related patents continuously from patent databases and then, *if present*, forwards the trend changes (alerts) along with corresponding patent documents, which create these trends to the user, who configures and requests the patent alert. PAS has a software application created for the "Patent Watch Departments" of the companies, which track the patent information for several purposes. The application currently serves as "desktop software" and it is easy to configure and use. It may be worthy to use PAS, for selecting a significant patent to iterate.

## 3.2 Step 2: Calculation of E/R Value for the Selected Patent

In this step, E/R value of the selected patent is calculated considering the novelty or novelties proposed by technology. For this purpose, the evaluation structure described in Sect. 4 is employed by the use of E/R matrix.

## 3.3 Step 3: Search for Novelty to Increase E/R Value

There is a variety of techniques used as creativity management tools for new product development process. These techniques are quite similar with special pros and cons of each [41]. Several creativity management techniques like "Theory of Inventive Problem Solving" (TRIZ), "Quality Function Deployment" (QFD) and "Cased Based Reasoning" (CBR) can be used to add value to the selected patent. However, it should be remarked that eco-innovation is different from general innovation and requires additional attributes of innovation towards sustainability. The goal of eco-innovation is to reduce environmental burden or achieve specific environmental performance objectives. Therefore, seven factors, which were presented as “acquisitions provided by the proposed novelty” in Sect. 4, should be considered and addressed during the idea generation.

### *3.4 Step 4: Decision on Adding/Removing of a Proposed Novelty to the Selected Product/Process or Service*

Decision about adding/removing of a novelty is performed by a simple benchmark among the E/R values of patented product and the proposed novelty. If the value for E/R is increased by the added proposed novelty, then it can be added, otherwise Step 3 can be repeated. It should also be noted that, even if a novelty is valuable to add to the existing product, it could be previously patented. Therefore a functional change of the existing product (towards a new patent) can be required [42].

## 4 Case Analysis: Green Buildings

Green building has been a developing market especially in the last 10 years. While research continues to define the costs and benefits of green buildings and some strategies to evaluate and achieve the highest benefits at the lowest costs, some questions stay in the center of those research directions. What is green building? How is it different? Is it better? What are the risks? How can we evaluate and analyze them? We will try to discuss these questions in this study based on some case studies.

After some research, there are at least 12 different definitions of green buildings catalogued on the internet, let’s look at some [43]. According to the U.S. Environmental Protection Agency, “green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building life-cycle from siting to design construction, operation, maintenance, renovation and deconstruction” [44]. Another definition is a short one that capitalizes on some main principles of green building: “building that is aimed at energy conservation, saving natural resources, and preserving the environment” [45] comes from Global Green Building, LLC. Some other definitions include characteristics of green buildings as promotion of energy conservation, creation of a healthy place to live, creation of environmentally sound construction [46], usage of internal recycling, renewable energy resources, recyclable or biodegradable construction materials, blending in the local environment [47]. Sometimes green buildings are referred to as “sustainable building” or “environmental building” [48].

The overall impact of the green building on human health and natural environment is reduced by:

- Efficient energy, water and other resources usage.
- Protection of occupant's health and improvement in productivity.
- Reduction of waste, pollution and environmental degradation.

"Green building" is a broad synergetic and multifaceted concept. The roots of green building in the United States arose from the needs and wants of more energy efficient and environmentally friendly construction [49]. The idea for sustainable development can be traced from the environmental pollution concerns and energy crisis of the 1970s. Green buildings combine lots of practices and techniques to ultimately reduce the impact on the environment. The emphasis is on using the renewable resources, better usage of sunlight (active solar, passive solar, photovoltaic techniques), rain gardens, rainwater utilization, green roofs, green concrete, etc.

The technologies in green building are constantly emerging and evolving and are focused in the areas of:

- Siting and structure design efficiency.
- Energy efficiency.
- Water efficiency.
- Materials efficiency.
- Indoor environmental quality enhancement.
- Operations and maintenance optimization.
- Waste and toxins reduction [49].

According to Statistical Summary on Buildings and their Impact on the Environment, buildings account for 38.9 % of total U.S. energy consumption in 2005, buildings account for 72 % of total U.S. electricity consumption in 2006 and this number is projected to rise by 75 % by 2025 [50]. In the United States, buildings contribute 38.9 % of nation's total carbon dioxide emissions [50]. On average, Americans spend about 90 % or more of their time indoors [50]. Some other striking examples of energy use, water use, land use, and other environmental and population facts are published in the above-mentioned summary. The need for improving sustainability of our environments, including buildings is evident.

With this emerging sustainability movement, the questions of how and why build green, as well as valuation and risk management, became some of the most serious questions among engineers, builders, economists, marketing and supply management, appraisers and technology management professionals.

Several grading systems worldwide exist in green building. They range from simple to chronologically complex, from prescriptive to performance based, even from design guidelines to EIAs (environmental impact assessments) [51]. They are usually classified as:

- First generation: nominal (pass/fail type): Those are usually prescriptive certification programs that judge against codes, standards, bylaws with limited focus on energy and indoor environmental quality.

- Second generation: (additive) (LEED, USA): Simple additive systems have appeared due to support from various government agencies with little scope for user-modification to reflect regional differences or individual preferences.
- Third generation (weighted additive): Those systems are inherently complex and lack objective basis. Weights are mostly judgmental or conscious-based and involve expert opinion to rank parameters and allocation based on analytic hierarchy process, statistical correlation and artificial neural networks [51].
- Others: More detailed representation of the grading systems for green buildings could be found in Table 1 [51].

In general, the rating systems for green buildings use some methodologies that allot credits for design features to improve sustainability [52]. Reductions in energy use, improvements in indoor air quality, etc. are the credits. Most of those rating systems are based on a measure of expected performance at design time, so the questions emerge, are those certified buildings living up to their expectations? According to the data by the New Buildings Institute and its analysis by Newscham [52], LEED buildings used statistically less energy than Commercial Building Energy Consumption Survey (CBECS) buildings: average savings ranged from 18 to 39 %, depending on parameters, but at the same time 28–35 % of individual LEED buildings used more energy per floor area then their matched CBECS counterparts.

Also, the grading systems don't include risks analysis, and if green buildings are here to stay, than all the project participants (architects, engineers, builders, marketers) need to be able to manage those process and project risks [53]. Factors like R&D capability, complexity of the product design and production process can have a huge impact on the whole green building construction. To avoid breakdowns, risks need to be managed; materials need to be well selected and application processes need to be chosen very carefully. Any neglect in choosing the right material can cause the whole project to fail. Recycled materials are highly needed, but because these materials are usually expensive, while mixing them with cheaper, weaker or overall inadequate resources may jeopardize the project. Moreover, design and good supervision play an important role when constructing a green building. So, green buildings have to be well designed, properly supervised, and have materials that meet the standards. Since the eco-innovations in green building could bring additional risks, we will analyze two case studies with the novel E/R measure proposed in this chapter.

## 4.1 Selection of the Cases

The selection of the cases was based on testing of the E/R methodology in two types of green buildings, which had different after-design outcomes despite their LEED certification. We focused on finding one building or building complex as an exemplary green building that continues to excel in green building standards and

**Table 1** Most popular grading systems for buildings

| Type | Years | Grading system | Developed by | Country |
|---|---|---|---|---|
| First generation | 1981 | R-2000 | Canadian Home Builders' Association (CHBA, Natural Resources Canada (NRC) | Canada |
| | 1989 | P-mark | Swedish National Testing and Research Institute (SP) | Sweden |
| | 1997 | ELO & EM scheme | Danish energy authority | Denmark |
| | 2001 | Energy Star | Environmental Protection Agency (EPA), and Department of Energy (DOE) | USA |
| Second generation | 2000 | Leadership in Energy and Environmental Design (LEED) | U.S. Green Building Council (USGBC) | USA |
| Third generation | 1990 | Building Research Establishment Environmental Assessment Method (BREEAM) | Building Research Establishment (BRE) Ltd | UK |
| | 1993 | Building Environment Performance Assessment Criteria (BEPAC) | Environmental research group, University of British Columbia | Canada |
| | 1996 | Hong Kong Building Environmental | HK-BEAM Society | Hong Kong |
| | 2001 | Housing Quality Assurance Law (HQAL) | Japanese Government | Japan |
| | 2002 | Green Building Tool (GBTool) | Sustainable Built Environment (iiSBC) | International |
| | 2002 | Global Environmental Method (GEM) | Global Alliance for Building Sustainability (GABS) | UK |
| | 2003 | Green Star | Green Building Council of Australia (GBCA) | Australia |
| | 2004 | Green Globes | The Green Building Initiative (GBI) | USA |
| | 2004 | Go Green, Go Green Plus | Building Owners and Manufactureres Association (BOMA) | Canada |
| | 2004 | Maintainability Scoring System (MSS) | Dapartment of Building, National University of Singapore (NUS) | Singapore |
| | 2005 | National Australian Built Environment Rating System (NABERS) | Department of the Environment and Heritage (DEH), commercialized by Department of Energy, Utilities and Sustainability (DEUS) | Australia |
| Others | 2004 | Comprehensive Assessment System for Building Environmental Efficiency (CASBEF) | Japan Sustainable Building Consortium (JSBC) | Japan |

the other one that failed to perform even though it passed the certification program. Knowledge of the outcomes may produce bias in our analysis, but it allows us to analyze whether E/R measure could capture the risks in those cases appropriately and be a reflective measure for the known after-design life of each building.

## *4.2 Green building—Case 1: The AMD Lone Star Campus in Oak Hill, Austin, Texas*

AMD lone star campus in Austin is a successful example of a green building. It was built in 2008 and achieved LEED® (Leadership in Energy and Environmental Design) Gold certification by the U.S. Green Building Council in January 2009 [54]. AMD now is considered the largest gold certified LEED® commercial building in Texas [55]. Its management succeeded in increasing efficiency, reducing energy, and water consumption. Moreover, AMD encourages its employees to adapt recycling habits by offering recycling stations at every building. Also, AMD encourages carpooling and usage of public transportation, which led to huge savings. Annual saving percentages reported by AMD usually exceed their original goals [56–59]. AMD conducted intensive and creative sessions with a team of ecological, architectural, engineering, and environmental building experts—known as a "charrette" process—to analyze the special and unique characteristics of the site in Oak Hill and identify specific methods to protect the environment, natural resources, and employees' health [56] (Table 2).

AMD Lone Star main focus was in the following areas:

### 4.2.1 Sustainable Sites

AMD worked closely with the Lady Bird Johnson Wildflower Center to restore disturbed areas to with 100 % native plants and protect existing habitats. Moreover they decreased the building area 20 % of the land allowable by zoning [56, 58]. In regard to light pollution, AMD worked to minimize the light coming from the building. This helped reduce the site's influence on nocturnal animal habitats [56, 58].

**Table 2** AMD Lone Star Project Information [59]

| Site area | 2,560,892 sq. ft. |
|---|---|
| Gross conditioned building (excluding garages) | 860,000 sq. ft. |
| Total impervious footprint (including garages, paved walkways, and drives) | 737,000 sq. ft. |
| Surface parking spaces | None |
| Structured parking spaces | 2,35 |
| Project cost (excluding site work, furnishing, and equipment) | $210,000,000 |
| Project completion | April 2008 |

### 4.2.2 Materials and Resources

Every building in AMD Lone Star has a recycling station. Also, the cafeteria separates food's waste so it can be used for fertilization [58]. AMD used about 20 % of recycled substances in their construction, 20 % of which were locally sourced [56]. More than 50 % of wood used was certified by Stewardship Council, which encourages responsible forest management [56, 58].

### 4.2.3 Water Efficiency

AMD used native plants for landscaping that require little watering. Also, applied low-flow water fixture could decrease the usage of water by the average office worker by 30 % [56].

### 4.2.4 Indoor Environmental Quality

Materials used in construction were eco-friendly, so the indoor environment would be as close to nature as possible. They used low-emitting adhesives and paints, eco-friendly carpets, wood, and agrifiber products. Also, ventilation systems used in AMD were set to meet or even exceed the outdoor air ventilation rates [56].

The building was designed so employees would have maximum outdoor views. Also, AMD installed a light reflector outside the building so it would bounce back more natural light. This helped improve indoor environment and decrease energy consumed by the lighting [56].

### 4.2.5 Energy and Atmosphere

AMD energy-efficient design helped reduce energy consumption by 15–20 % (compared to building with similar size) through many procedures such as proper building orientation, efficient HVAC equipment, automated switching and dimming, R-30 roofs, and glazing and shading devices [56]. AMD used the most technology available in energy-efficient air conditioning, providing about 10 % of the water in evaporation cooling through the rainwater collection [56]. Moreover, AMD is powered by 100 % by Austin Energy's Green Choice® electricity, which generates its electricity from clean, renewable energy sources [58].

### 4.2.6 Innovation in Design

AMD rainwater collection system is considered one of the largest in the world. It has a capacity of more than 1.2 million gallons. The water collected by this method is used for cooling towers and irrigation [56].

Summary of main AMD Lone Star green building accomplishments:

- Decreased water usage—rain system through an innovative collection and redistribution methods used; consumption of water decreased 30 % compared to traditional building [56, 59].
- Efficient Recycling—used 20 % recycled materials in their construction, which reduced the use of raw materials; recycled 75 % of construction waste; provided recycling stations in every building (for paper, cardboard, glass, plastic, and metal), and recycling food waste for composting [56].
- Reduced energy consumption—reduced energy consumed by lightning system through proper orientation and maximizing natural light coming from windows, leading to reduction in $CO_2$ emissions by 15–20 % compared to a traditional building [56].

## 4.3 *Green building—Case 2: The Courthouse Square*

The Court Square Transit Mall is a green construction that shows issues, problems, and failure in green building standards. This mall was built in 2000, in downtown Salem, Oregon, and failed in 2010. [60] The five-story building consists of county offices, a transit station, retail stores, and a north part for future expansion. Courthouse Square cost 34 million dollars including 9.8 million dollars from a federal grant [60–62]. Significant amount of concrete has been used for construction of this building, which is approximately 160,000 square feet plus the underground parking. There is 90 miles of telephone and data cable in the building and enough concrete in Courthouse Square for a sidewalk from Salem to Portland [60–62].

The Courthouse building had received U.S Green Building Council's Leadership in Energy and Environmental certification in 2000 [63]. The first problems started to appear in 2008, on the first floor when the tiles started to pop up [61]. Two years later, in 2010, engineers asked the occupants to evacuate the building, since it was too dangerous to stay in it. Some experts estimated that it will take more money to repair Courthouse Square than it cost to build the building in the first place [61].

When architects and engineers went through an investigation, they found several problems:

### 4.3.1 Design Issues

The building in general was poorly designed, full of errors, and shoddily constructed [62].

Inappropriate materials have been used in the construction. In the Courthouse Square, the risks of new materials impacting the design and strength of materials were not accounted for. Later on, further inspections of the building revealed that 35 of the construction columns were supporting more weight than they could tolerate and the code allows, which ultimately led to building evacuation [63].

As we mentioned earlier, some problems, identified in the building in 2008, appeared not significant enough to engineers. Furthermore, later in 2010, problems got more serious, when a loud noise resembling explosion, as a result of a ruptured cable, was heard in the building, causing floor vibrations [62]. There were several steel cables in the concrete slabs in the floor. These cables were used for back-up supports, and also to make the slabs stronger. However, breaking one of them was a big threat to the building [62, 63].

### 4.3.2 Problems with Support Structures

One big threat that made engineers move people out of the building was the "punching shear" [64]. This problem will cause the construction's columns to punch through slabs, and then force the whole building to collapse. Because most of the cracks appeared in the floor and the ceiling, it was more likely that punching sheer would happen. The weight of the floor slab could punch through the supporting column, which means the floor could fall over the supporting base at any time [65]. Finally, after an extensive check of 19 columns, the engineers found one column that was going through the punching shear problem [64].

### 4.3.3 Problems with the Concrete

One of the materials used in Courthouse Square was concrete. After some tests on the concrete, engineers found out that the concrete in the building was not strong enough, and did not meet the requirements. One test showed that the concrete in the building could handle an average of 4,151 pound per square inch (PSI) while it needed to handle 5,000 PSI [64].

Sub-standard concrete was used on the third floor, where there was a slab that could handle just 3,500 PSI [64]. So, the concrete did not meet the standards. In all types of buildings, deflection sometimes can be considered normal, unless it exceeded the deflection code. However, the Courthouse had a higher deflection than the allowed code in the floor [64]. The deflection for concrete slabs in this building was 4 inch while just 1.9 inch was allowed [64]. Also, the tests on the concrete showed that some garbage was used in the creation process whether for the purpose of reusing/recycling or reduction in costs [60].

The type of concrete caused another problem and it was one of the main issues in the construction. For example, the engineers detected air pockets and found out that this kind of concrete should have not been used for Courthouse building because it is usually used for outdoor constructions, such as sidewalks. And it is not suitable for indoor and internal building constructions [64].

### 4.3.4 Poor Supervision

After the Courthouse's failure, engineers believed that the building had poor supervision during its construction process [66]. Overall organizational and performance issues on top of the design issues could have contributed to the overall failure.

### 4.3.5 Additional Structural and Non-Structural Problems

Failures accrued in different parts of the building, such as leaking in windows and cracks in interior walls, bending frames and deformations of steel landings [64].

## *4.4 Calculation of E/R Value for Case 1: The AMD Lone Star Campus in Oak Hill, Austin, Texas*

To measure the benefits or the processes of any novel eco-friendly products, we use seven eco-efficiency elements have been defined by the World Business Council for Sustainable Development (WBCSD) [33] and 8 NPD risks described in this chapter by applying the following equations [34], which are implemented into the created Excel spreadsheet matrix (Fig. 3):

| E\R | CPD | SEP | RDC | PES | CPP | SES | SPP | PRC | E |
|---|---|---|---|---|---|---|---|---|---|
| E1 (Material reduction) | 1 | | | | | | | | 1 |
| E2 (Energy reduction) | | | | | 1 | | | | 1 |
| E3 (Toxicity reduction) | | | | | 1 | | | | 1 |
| E4 (Material retrieval) | | | | 1 | | 1 | | | 0.5 |
| E5 (Resource sustainable) | | | | 1 | | 1 | 1 | 1 | 0.25 |
| E6 (Product durability) | 1 | | | | | | | | 1 |
| E7 (Product service) | | 1 | | | 1 | | 1 | | 0.333333333 |
| | | | | | | | | E/R Value | 0.726190476 |

**Fig. 3** AMD Lone Star – E/R Evaluation Matrix

$$\mathrm{E/R} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{i=7}} \#\ \text{of risk factors provided by the proposed novelty by acquisition}\ \mathrm{E_i}}{7}$$

OR:

$$E/R = \frac{\sum_{i=1}^{7} E/R_i}{7} = \frac{\sum_{i=1}^{7} \frac{1}{\sum_{j=1}^{k} R_j}}{7}$$

where:

$$E/R_i = \frac{1}{\sum_{j=1}^{k} R_j},\ i = \overline{1\ldots7},\ j = \overline{1\ldots8},\ 1 \le k \le j$$

The eco-innovation elements (or benefits) that have been found through our analysis of the AMD building were in:

1. Sustainable sites (used: E5, E7).
2. Materials and resources (E1 maybe E5).
3. Water efficiency (E3, E4, E7).
4. Indoor environmental quality (E2, E5).
5. Energy and atmosphere (E2, E7).
6. Innovation in design (E6, E7).

As we saw from the results and from that successful model, the AMD building didn't have that many risks that can affect the eco-innovation benefits. For example, R&D didn't have any difficulties for reduction of toxicity and decrease of energy usage.

The reduction of impact on local water ecology represented one of the main parts to reduce toxicity. Also the reduction of use in raw materials and construction waste were some of the key elements of retrieval and recyclability.

1. Complexity of the Product Design (CPD): We believed that the risks of the complexity of AMD green building could have impacted material reduction and product durability.
2. Similarity of the Existing Product (SEP): Some of the elements like the material reduction didn't have that many problems for the engineers, who designed the building. The engineers and architects were not especially limited by costs or cheaper materials. We didn't consider large impacts of this risk on the benefits. We considered new product designs impacting product service.
3. R&D Capability (RDC): Didn't have risks especially with a successful model and highly experienced R&D engineers, architects and designers. "Charrette" method of getting feedback was used in the design and production process.

4. Supplier Performance (PES): We didn't have much information about the suppliers in the project and believe that since the project was successful, the risks could have had impact in two places: resource sustainability and material retrieval.
5. Complexity of the Production Process (CPP): The production process is more complex than in the regular buildings, the impact of this risk is considered in the following categories: energy reduction, toxicity reduction and product service.
6. Similarity of the Existing Supply (SES): The risk would impact mostly in material retrieval and resources sustainability since the materials and equipment used could have been completely different than the ones used in common buildings.
7. Similarity of the Production Process (SPP): The production process would be different, so the risk might be present in product service and resource sustainability.
8. Production Capability (PRC): AMD hired qualified and capable production resources (engineers, architects, builders etc.) and companies, so the risk in production capability would impact just resource sustainability.

## *4.5 Calculation of E/R Value for Case 1: The Courthouse Square*

The eco-innovation elements (or benefits) that have been found through our analysis of the AMD building were in:

1. Sustainable sites (n/a).
2. Materials and resources (n/a).
3. Water efficiency (used: E3, E4, E7).
4. Indoor environmental quality (n/a).
5. Energy and atmosphere (used: E2).
6. Innovation in design (n/a).

The Complexity of the Equipment and their design took a big effect on all of the Elements. For example, to reduce the building's energy use, the engineers had to install and design new equipment and tools for that specific reason, so they can save power. The same thing happened to the rest of the elements (Material retrieval, Resource sustainable … etc.).

The failure of the building and then shutdown can be considered as examples of the consequences of the risks volume. The non-sustainable site and the building's poor innovation in design were the results that made a huge impact on the estimated numbers that we had used and then got implemented on the E/R evaluation matrix (Fig. 4).

1. Complexity of the Product Design (CPD): This risk has been found in all of the seven elements. The Courthouse Square a complex with a bus mall and a

| E\R | CPD | SEP | RDC | PES | CPP | SES | SPP | PRC | E |
|---|---|---|---|---|---|---|---|---|---|
| E1 (Material reduction) | 1 | | | 1 | 1 | 1 | | 1 | 0.2 |
| E2 (Energy reduction) | 1 | | 1 | | | | | | 0.5 |
| E3 (Toxicity reduction) | 1 | | 1 | 1 | | | | | 0.333333333 |
| E4 (Material retrieval) | 1 | | 1 | 1 | 1 | | 1 | 1 | 0.166666667 |
| E5 (Resource sustainable) | 1 | 1 | 1 | 1 | 1 | | | 1 | 0.166666667 |
| E6 (Product durability) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.125 |
| E7 (Product service) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.125 |
| | | | | | | | | E/R Value | 0.230952381 |

**Fig. 4** Salem Courthouse Square—E/R Evaluation Matrix

parking structure underground. For example, in reduction of energy, toxicity of the material, complexity can be considered as one of the main obstacles.

2. Similarity of the Existing Product (SEP): Some of the elements, like the material reduction, didn't have that much of problems for the engineers who designed the building. The building had low to medium similarity to the existing building since it was a new green building.
3. R&D Capability (RDC): From the R&D perspective, building a new green construction from scratch can definitely be accompanied with a lot of issues in creating benefits.
4. Supplier Performance (PES): Some new supplied materials and their applications (concrete) as well as equipment brought more risks to the process.
5. Complexity of the Production Process (CPP): The production process seemed to be more complex than the regular platforms, therefore the above indicated risks have been considered.
6. Similarity of the Existing Supply (SES): Issues were found mostly in material reduction, product durability and product service.
7. Similarity of the Production Process (SPP): Since the production process was different in a new green building construction, this item should be considered as a risk in attaining some of the benefits like material retrieval, product durability and product service.
8. Production Capability (PRC): This risk category impacts the benefits from green building directly. The huge failure of the building is a clear example of the constructors' incapability. Material reduction and retrieval as well as resource sustainability, product durability and product service are impacted by the production capability. The companies involved were not capable of building a successful structure.

## 4.6 Results of E/R Values in Two Green Building Cases

From the E/R matrix calculation results, the values for the AMD case study and the Courthouse were different. To reach the ideal situation, the E/R value needs to be $\sim 1$. The closest the value to 1, the better and the more benefits we can get out of the project and the less risks associated with each eco-innovation are.

From the E/R matrix calculations:

The AMD E/R value = $\underline{0.726}$ is closer to the ideal situation compared to the Courthouse E/R value = $\underline{0.231}$.

According to the formulas, the largest E/R value means less risk and more benefit. The Courthouse's failed because its risks greatly exceeded the benefits, on the other hand the AMD building had more benefits/less risks.

We have used various assumptions while calculating risks, since we didn't have enough data and expertize available, and our judgment of risks could be biased and perceived on the research that we did. More rigorous testing of the methodology with the right expertise and knowledge of the subject could be applied. However, we believe that E/R measure could be applied to green buildings, especially prior to the initialization of NPD process. In our case we tested this novel E/R measure post-design with known outcomes, so our selection of risk could be impacted by the post-mortem knowledge. It would be best to apply E/R during the fuzzy front end of the project and apply risk mitigation or risk management to lower the risks associated with eco-innovations.

## 4.7 Future Research

We examined the proposed novel E/R measure for two cases of green buildings. One of them is based on a successful building, another one—on a failed building. For future studies we would recommend applying E/R methodology to more green buildings, possibly a sample of green buildings before their construction, and then analyzing them after.

It would be good to see the usage of E/R methodology in some grading/certification systems in the future at least as a test system in addition to their grading framework. Measures of risk for eco-innovations should be encouraged in evaluating green building design.

Below we propose various measures of risks as well as E/R measure based on severity and probability of risk. Future testing and implementation of those formulas in real cases is encouraged. By adding additional dimensions of risk as severity and probability, we believe in the added benefit to the E/R methodology. It could be a very useful tool if such data could be obtained or calculated before the design of the building. Convenient tool in Excel is also proposed for an easy calculation of those measures.

Ri ratio (7.4), (7.5) measures the ratio of risk to the total possible risk for each acquisition and total.

1-R ratio (7.6), (7.7) measures the non-risk ratio.

E/R [P, S] (7.8), (7.9) measures the E/R ratio, based on the probability and severity of risk (sum of product of P and S for each risk).

$$R_i \text{ ratio} = \frac{\sum_{j=1}^{k} R_j}{8}$$

$$R \text{ ratio} = \frac{\%R_i}{7} = \frac{\sum_{j=1}^{k} R_j}{56}$$

$$1 - R_i \text{ ratio} = 1 - \frac{\sum_{j=1}^{k} R_j}{8}$$

$$1 - R \text{ ratio} = \frac{\sum_{i=1}^{7} \left[ 1 - \frac{\sum_{j=1}^{k} R_j}{8} \right]}{7}$$

$$E/R[P, S] = \frac{\sum_{i=1}^{7} \left[ \frac{1}{\sum_{j=1}^{k} P_{Rj} S_{Rj}} \right]}{7}$$

$$E/R[P, S]_i = \frac{1}{\sum_{j=1}^{k} P_{Rj} S_{Rj}}$$

Our new expanded E/R calculator (Fig. 5) will handle all proposed measures of E/R and will calculate correctly, whether the numbers that will be added represent probabilities or just risks (1 s) as a measure of E/R. For E/R (based on expert evaluations of risks versus every eco-benefit), the model assumes that at least one risk value (1) is present at each “acquisition of the proposed novelty”. One is entered if the risk is anticipated. (Numbers go into columns with 7 green three-letter risk abbreviations). There are future possibilities to further improve the calculator, making it a stand-alone application, assigning macros in VBA etc.

All the calculations and assumptions are based on 8 types of risk and 7 types of eco-innovation acquisitions or values. Future research could be done to personalize the methodology by having particular applicable risks and values, or even specific weight assigned to them.

| | CPD | | SEP | | RDC | | PES | | CPP | | SES | | SPP | | PRC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E\R | $P_{CPD}$ | $S_{cpd}$ | $P_{SEP}$ | $S_{SEP}$ | $P_{RDC}$ | $S_{RDC}$ | $P_{PES}$ | $S_{PES}$ | $P_{CPP}$ | $S_{CPP}$ | $P_{SES}$ | $S_{SES}$ | $P_{SPP}$ | $S_{SPP}$ | $P_{PRC}$ | $S_{PRC}$ | $E/R_i$ | R ratio | (1-R ratio) | $E/R_{(P,S)}$ |
| E1 (Material reduction) | 0.5 | 0.5 | | | | | | | | | | | | | | | 1 | 0.13 | 0.88 | 4 |
| E2 (Energy reduction) | 0.5 | 1 | | | | | | | | | | | | | | | 1 | 0.13 | 0.88 | 2 |
| E3 (Toxicity reduction) | 0.5 | 1 | | | 0.2 | 0.5 | | | | | | | | | | | 0.5 | 0.25 | 0.75 | 1.667 |
| E4 (Material retrieval) | 0.5 | 1 | | | 1 | 0.8 | | | | | | | | | | | 0.5 | 0.25 | 0.75 | 0.769 |
| E5 (Resource sustainable | 0.5 | 1 | | | | | | | | | 1 | 1 | | | | | 0.5 | 0.25 | 0.75 | 0.667 |
| E6 (Product durability) | 0.5 | 1 | | | | | | | | | | | | | | | 1 | 0.13 | 0.88 | 2 |
| E7 (Product service) | 0.5 | 1 | | | | | | | | | | | | | | | 1 | 0.13 | 0.88 | 2 |
| | | | | | | | | | | | | | | | E/R Values | | 0.79 | 0.18 | 0.82 | 1.872 |

**Fig. 5** Expanded E/R calculator

It would be valuable to testing E/R and E/R with probabilities and severities against other risk/benefits methodologies with the reference to green buildings.

## 5 Conclusions

"Sustainability" has been an emerging concept of today's exhausting world. It has been at the core of governments and industries policy. Since sustainability has a long-term focus, beyond the commercialism of projects, products, processes or systems, a holistic approach has been searched for developing desirable and technically, institutionally, politically and culturally significant product/processes and services. Uncertainty in eco-innovation process has made it difficult to find a holistic approach ensuring all constraints and expectations. Therefore, policy makers preferred developing very conservative policies since they cannot handle the uncertainty. On the other hand, engineers who are involved in developing new technologies are also faced with an ethical dilemma. The dilemma has arisen due to the conflict between responsibility of an engineer to an employer and a responsibility to the welfare of the wider community.

In this chapter, an overview of the state-of-the-art of concepts and frameworks used for assuring the "Sustainable Development" through green/eco-innovation has been presented. Subsequently, a green/eco-innovation framework incorporating the uncertainties and acquisitions has been proposed. The proposed framework presents a practical and useful guideline for eco-innovation through new product development. On the other hand, it is well worth to point out that the proposed framework still in its infancy and it requires further improving and extending. As a future study, various tools, techniques and methodologies can also be integrated into the framework which can hopefully create better solutions for NPD process. In addition to these expectations, the proposed framework should be tested via employing it to some cases.

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# Analysis of Demand Side Management Products at Residential Sites: Case of Pacific Northwest U.S.

**Ibrahim Iskin and Tugrul Daim**

**Abstract** This paper provides a quantitative approach to determine important product features that are to be included in smart thermostats. This approach is expected to help decision makers manage product design process by utilizing feedback from customer and expert focus groups. Proposed approach is also expected to help managers review competing products in the market and shape future product design specifications. Data used in the assessment model have been gathered by surveying 22 potential customers who have been living in residential areas, and a group of experts who have been working as product design engineers. Significant findings as well as weak points of the proposed approach have been discovered, and future work initiatives have been proposed.

## 1 Introduction

Annual Energy Outlook 2008 (AEO2008), a report by the Energy Information Administration, projects a steady demand growth of 0.7 % per year through 2030 [1]. Projected growth in demand has spurned several initiatives aimed at forestalling potential shortages and outages caused by supply–demand mismatches. One such initiative is demand side management (DSM), which essentially focuses on influencing energy consumption patterns of end users especially during peak times when energy supply systems are strained. Moreover, our society today has become more sensitive to negative impacts of energy systems on the environment, and as a result consumers today are more aware of the need to conserve energy.

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DSM provides an opportunity to meet needs of today's energy-hungry yet environmentally aware society.

This section is going to be based on a case company, which is named as "ABC" due to confidentiality provisions. ABC is a startup company founded in 2006, aiming to position itself to make an impact in the DSM market. ABC currently focuses on developing an innovative smart thermostat product and a complementary web service platform. One of the issues that ABC currently faces is the difficulty in determining product features to include in their new product and optimum way to forward their product over competing alternatives. This report highlights investigative research conducted on identification and selection of potential product features; results and their potential implications are discussed. Finally, optimum product features are proposed as recommendations.

## 2 Demand Side Management

Forecasting electricity loads had reached a comfortable state of performance in the years preceding the recent waves of industry restructuring [2]. Adaptive time-series techniques based upon ARIMA, Kalman filtering, or spectral methods were sufficiently accurate in the short term for operational purposes, achieving errors of 1–2 % [3]. The technology is now providing the opportunity for consumers to respond to fluctuation in price by lowering their energy consumption during peak times. Using this strategy power companies now have the capability to even out the demand for power generation with simple economics rather than building physical power plants. Kirschen states, most consumers, with the possible exception of the largest ones, do not have the financial incentive and the expertise required to contribute effectively to such a complex and time-consuming task [4]. Recent experience in California made clear that introducing competition on the supply side while shielding the demand from liberalized prices seriously distorts the market [5].

## 3 Technology Assessment Process

To properly assess a technology there are several steps that must be performed. The first step is to identify the problem, and hardest part of this is gap analysis. Gap analysis is to be followed by a technology environment analysis, and evaluation criteria and methodology. Using these techniques a proper framework or model can be created of the technology in question.

### *3.1 Case Company Gap Analysis*

In order to determine the best way forward, a gap analysis needs to be performed. Gap analysis is a business resource assessment tool enabling a company to compare its actual performance with its potential performance [6]. At its core there are two questions:

- Where is company ABC among the competitors?
- What is the optimum positioning for company ABC?

The gap is defined as: gap = capabilities—needs.

### 3.1.1 Capabilities of Case Product

Among ABC's key products is Product™. The capabilities of Product™ are broken down into capabilities for residents and capabilities for energy distributors.

### 3.1.2 Capabilities for Residents

Case company ABC currently has two products, which are referred as "Product™" and "Platform™ Core" due to confidentiality provisions. Product™ is a packaged device whereas Platform™ Core is a web platform, which enables customers to manage their energy usage. System provides optimum trade-off between cost savings and comfort, reducing electric bills by up to 25 % during critical times. Users have the ability to use cell phone to control the settings as well. Internet-based solutions of ABC provide the user-friendly setup, control and reliability that are critical to end-user acceptance, while delivering the security and extensibility that the customers require.

The system moderates heating and A/C temperature settings through the use of an intelligent thermostat that can be controlled from our web interface through the ABC Platform™ Core. Intelligent gateway is a small hardware device that communicates wirelessly, using 802.15.4/ZigBee and other protocols, with several devices within the home, including thermostats, load control modules and other home automation devices. The Platform™ Core performs the on-site communication work, coordinating these devices through the Internet and communicating with the data center [7].

### 3.1.3 Capabilities for the Energy Businesses: Aggregators, Electricity Generation and Distribution Business

Since Product™ uses the customers' existing broadband connections, it can provide demand response and energy efficiency capabilities. This provides a cost-effective way for energy business to integrate a solution for small site management into their existing demand response systems. Integrating this solution can provide a competitive advantage against other aggregators. Product™ and its underlying platform Platform™ Core have been designed for integration into energy management companies' existing solutions.

### 3.1.4 Needs of Product$^{TM}$

**Needs for Residents:**
Residents use Product$^{TM}$ to get cost savings and comfort within the facilities. However, to obtain the advantage, they need to learn how to use it as a skill. What they need is not only the benefit to save energy but also the convenience as much as possible the product can provide. They would rather to have one device to control all the device of the home site than to have separate devices for different controls. So they hope that the product can integrate more features such as fire control, security control, irrigation control, gas leaking control etc. In short, they need a gateway for them to control all the home facilities. It might be a website or telephone service for them [8]. Residents also need more remote means to control devices in their homes. Besides the website, they also need to have more connectivity options like PC, telephone, SMS etc. to access Product$^{TM}$. The users hope that Product$^{TM}$ users hope that the device can be more intelligent in operation of home devices. For example, the users hope that the energy consumption can be as low as possible when there is no one in the house.

**Needs of Energy Businesses:**
Aggregators, electricity generation and distribution businesses all require information about amount of energy consumed by each subscriber at a given time, especially at peak demand time. That enable them to accurate forecast the energy needed down to the substation level as well as make them charge at different prices during different time. The information, which Product$^{TM}$ will provide, is the input for the Energy Businesses' information system. In order to cooperate with the other parts of the IS, the incoming data must be integrated into the system of energy businesses. A data transfer interface is needed to do this.

In order to reduce the energy consumption in the peak time, the Product$^{TM}$ also needs to control the home facilities to the mode of saving energy. This capability need the 2-way Demand Response because that we not only need to give information for to the energy businesses but also need to respond to the different charge in different time in order to get the highest energy usage efficiency.

### 3.1.5 Technology Gaps of ABC

To sum up, the technology gaps of ABC includes:

- More features integrated into the product
- More communication means to access the home facilities
- Automated control of the home devices
- Ability to measure the consumed energy in given time periods
- Integration with the system of energy businesses
- 2-way demand response to control home energy consumption.

## 3.2 Smart Thermostat Environment Analysis

### 3.2.1 Stakeholders

The smart thermostat technology model has opened up new fronts in the relationship between energy producers, distributors and consumers. Currently, there is potential for interactive response to changes on all sides. Consumers have an opportunity to monitor and adjust their consumption. Energy distributors such as; energy utilities and aggregators currently can use energy data from smart thermostats and advanced metering systems to predict energy patterns, buy energy at better rates and deliver savings to their customers. In 2006, one such utility, PJM Interconnection that serves 13 states and the District of Columbia, realized 2046 MW resulting in payments of $650 million to customers who curtailed their energy usage as part of demand response programs [9].

Many other stakeholders are also strategically aligning themselves by forming alliances that share ideas to promote innovation in the industry. Smart Energy Alliance is a group of technology companies including Capgemini, Cisco, GE Energy, HP, Intel, and Oracle. Smart Energy Alliance has a goal of implementing Supervisory Control and Data Acquisition (SCADA) systems that give customers more freedom to manage their energy consumption, given the eventuality of smart metering and smart thermostat technology [10]. Another example of this is The NewEnergy Alliance which brings together the technologies, manufacturers, engineers, and service providers across the energy, IT, and building systems industries. The group's members are involved in developing and implementing complementary solutions and technologies to deliver sustainable energy goals for every type of building and customer. A key goal of the alliance is to help empower and create immediate revenue opportunities for members who wish to directly participate in demand response with their products, services and technologies. Another goal for such alliances is to develop and strengthen industry wide standards for home automation. Currently, there are several different communication protocols used by different manufacturers which could lead to interoperability issues.

### 3.2.2 Market Forecasts

Thermostat market has been steadily increasing. Frost & Sullivan Research group, an international marketing consulting and training company that has done extensive research on the North American thermostat market reports that the market totaled revenues worth $520.1 million in 2002 and has the potential to expand to $754.4 million by 2009. The majority of revenues come from the booming retrofitting segment [11]. The report also notes that many of the participants in the market are looking to maximize this opportunity by exploring novel applications for re-fitted thermostats. These novel applications include the complementary features and capabilities such as demand side management. Other research firms such as Forester research, another of the world's leading independent technology and market research companies, states that it expects IT environment monitoring to become a $11 billion industry by the year 2010. Environmental monitoring variables include:

- Temperature (high/low)
- Main and UPS power (interruptions)
- Flooding/water (water leaks, air conditioning condensation)
- Humidity (high and low)
- Smoke/fire
- Room entry/motion
- Airflow (A/C or fan status).

There are various different smart thermostat options available to consumers in the market. They offer a variety of technology features such as; electricity controls, water controls, in home display interfaces, phone interface, web interfaces, fire monitors, appliance control, gas leak monitors, among others. The direct competitors for ABC are other smart thermostat manufacturers like Ecobee®, Proliphix® and Venstar® that offer different combinations of the features in addition to basic thermostat control. They also implement different technologies to interface with the additional modules. Table below gives a brief technology survey of some of the competitors in the smart thermostat market of the different technologies (Table 1).

With such a wide array of technology options and providers all competing for market share and industry recognition it can be challenging to determine the best way forward for the company. The situation is further complicated by the fact that recent years have seen a rapid increase in innovations in the industry. To help determine where the real value lies for ABC, in the smart thermostat market, regular assessments may be may be needed to help guide the company decisions and overall strategy.

It is important to note that there are a few off the shelf programmable thermostats that currently retail at about $100 dollars such as; the Rite temp 6000 series, which offer additional features like fan and humidity control. Technology curve for these products tends to trend up slowly by integrating additional features

**Table 1** Technology survey

| Company | Proliphix | Homeseer | Aprilaire | Carrier | Venstar | ECOBEE | ABC |
|---|---|---|---|---|---|---|---|
| Cost | $449.99 | $344.95 | $270.95 | $3000 | $124 | $385 | $395 |
| Thermostat | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| connection | CAT5 | Z-Wave | RS485 | SkyTel | Phone Line | Wi-Fi, Zigbee | Wi-Fi, Zigbee |
| Additional control | None | Lamp modules | None | Special dampers | | Humidity | |
| Additional connectivity | Web-portal | Web-portal | None | Infinity furnace | Voice recognition/synthesis | Web-portal | Web portal |

with minimal or no increase in price. There are also some technologies in the building automation industry that offer a complete suite of control options including thermostat control and may have characteristics of disruptive technologies for the thermostat market.

### 3.2.3 Barriers to Pervasive Adoption of Smart Thermostats

Even though the market for smart thermostats has steadily grown, there are some barriers that exist to the widespread adoption of the technology. Several different reports have made an attempt to identify and address these barriers. One such report is the Residential Energy Conservation report prepared by request from the Technology Assessment Board at the Office of Technology Assessment (OTA) [11]. The report cites ease of use and cost, particularly life cycle cost as large barriers to the widespread adoption of smart thermostats. Another barrier identified in the report is that many consumers lack practical knowledge about how to accomplish conservation using existing technology options. This represents barrier to the diffusion of innovations. This effect is compounded further when introduction to a new idea or innovation is involved. Innovations and new ideas often involve uncertainty and a lot of misinformation or no information. There are five stages in the decision process, which are knowledge, persuasion, decision, implementation, and confirmation [12]. Knowledge of the options is an important first step in getting a technology to be widely adopted. Subsequent communication channels further promote the adoption of the technology.

## *3.3 Evaluation Criteria and Methodologies*

According to technology acceptance model perceived usefulness and ease of use are important determinants for customers to adopt a technology [13]. In our study we regarded "Savings" and "Additional Features" as sub parts of "Perceived Usefulness" as these are the competitive advantages that smart grid appliance developers focus on. We regarded "Ease of Use" itself as a determinant in the model.

It was expected that "Cost" would be an important factor in deciding adoption of a technology or a product. In the literature many researchers included this variable in their studies [14].

From several meetings with the company ABC's Vice President of Business Development, two major determinants important in smart grid technology field have been identified. These are "Service Reliability" and "Additional Features" [15].

Service reliability is considered to be important because many of the smart grid appliances use online communication, which makes their systems vulnerable to cyber attacks and hacking issues. At this point, it becomes very important to protect the system from attacks by the outsiders [15]. Connection availability is considered to be important because of potential discontinuities in communication. At this point ability to communicate in multiple ways becomes important so as to provide continuing service. Several communication ways have been added by reviewing existing products in the market. These are internet, SMS, mobile phone and telephone connections [16].

To gain a deeper understanding in additional features existing product features have been reviewed in the field and identified the following features, which are integration with water control, integration with home appliances, light control, fire control, phone control, fire control, security control, mode control, gas leakage control, PC control, and in home display control [16].

Accordingly, several major determinants determined to be effective in providing competitive advantage have been identified. These determinants are cost of the product, savings that the product provides, product ease of use, service reliability, and additional product features. As analysis specifically focuses on smart grid applications we have created some sub headings for each major heading to provide deeper understanding of the major determinants.

All in all, these sub determinants for each major determinant can be seen below.

- Cost: Installation cost, product cost and maintaining cost.
- Savings: Energy efficiency savings and demand response savings.
- Ease of Use: Ease of installation, interface, and personalization.
- Service Reliability: Security and connection availability.
- Additional Features: Integration with water control, integration with home appliances, light control, fire control, phone control, fire control, security control, mode control, gas leakage control, PC control and in home display control.

Refer to Appendix: Explanations of Additional Features to see the definitions of the features.

By using both major and sub determinants a model, which is expected to prioritize customer, desires from smart grid appliances have been designed. Please refer to figure below to have a better understanding in the relationships between determinants.

### 3.3.1 Methodology

Two surveys; one of which consists of eight questions prepared for potential customers, and another survey made of single question prepared for experts to evaluate competitive products; have been developed. Surveys were sent through e-mails and got the responses back in the same way. For potential customer survey, 22 responses have been received from people who live in residential areas and are interested in owning a smart thermostat system. For expert survey, needed data was gathered from experts who have been employed as product development engineers in the field.

Mix of pair wise comparison and scoring method was used for judgment quantification purposes. It is expected that the proposed model would show quick picture of competitive advantage profiles of each product as well as customer expectations from smart grid appliances in the energy saving technology field.

### 3.3.2 Assessment of the Determinants

As seen from the Fig. 1 above there is several sub and major determinants, which have hierarchical relationship. To find out the quantitative weights of each major determinant (orange colored variables in the figure above) and each sub determinant (yellow colored variables in the figure above)—except the ones under "Additional Features"—pair wise comparison technique was used.

It was found unpractical to pair wise compare 12 features under "Additional Features" by considering the fact that focus group would not be able to keep its concentration fresh and give consistent responses. With this thought in mind it was also aimed to cut down the effort for assessing the interface types under "Interface" and connection types under "Connection Availability". Because of this reason scoring technique was used instead of pair wise comparison technique for assessing the variables colored in blue.

After finding relative weights of each major and sub determinant weights of "Interface", "Connection Availability" and "Additional Features" to were required to be divided between sub features so that weights of all determinants and features in the model could be calculated. Below you can find related information about division of the weights.

To assess the features under "Interface" score of "Interface" was divided between "Website", "Cell Phone", "PC", and "Special Device".

To assess the features under "Connection Availability" the score of "Connection Availability" was divided between "Internet", "SMS", "Mobile Phone", and "Telephone".

To assess the features under "Additional Features" score of "Additional Features" was divided between "Integration with Water Control", "Integration with Home Appliances", "Light Control", "Fire control", "Phone Control", "Fire Control", "Security Control", "Mode Control", "Gas Leakage Control", "PC Control" and "In Home Display Control".

### 3.3.3 Assessment of the Competitor Products

In the meetings with Vice President of Business Development, a list of competitive products in the smart grid technology field was created to compare with ABC's product. Competing products were chosen among various products according to their performance in major determinants that are proposed to be important to residential customers. By assessing the products it is aimed to have enough data to calculate how much desirable each product is for each variable in the model.

A combination of two approaches was used to assess the products. One approach is to assess the products by using pair wise comparison, and the other one is to score the products by depending on whether they support a specific feature or not.

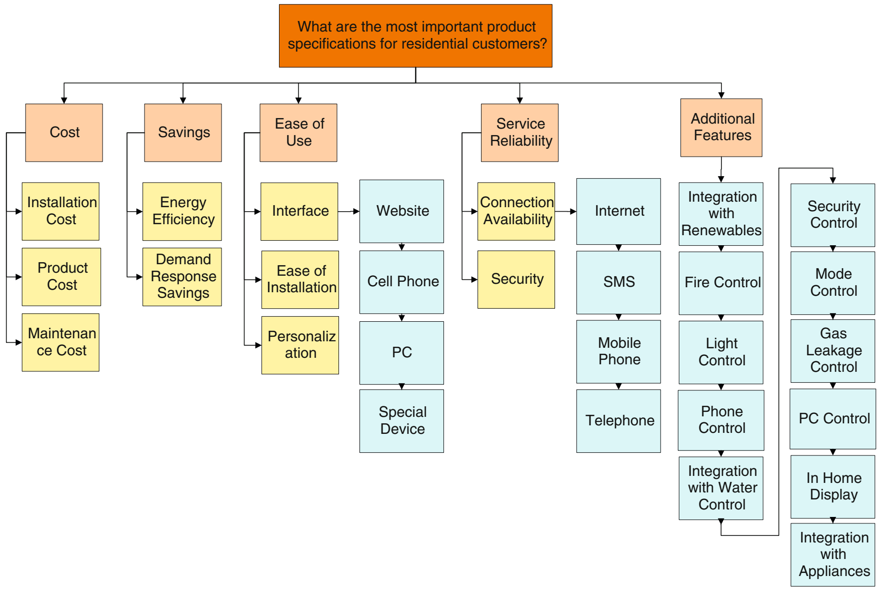


**Fig. 1** Model of feature breakdown

Pair wise comparison method was applied to assess the relative performance of each product in terms of "Installation Cost", "Product Cost", "Maintenance Cost", "Energy Efficiency", "Demand Response Savings", and "Ease of Installation".

Scoring method was applied to assess each product in terms of the interface types under "Interface", "Personalization", the connection types under "Connection Availability", "Security" and the features under "Additional Features." For example; if Product A helps users to personalize their product features then Product A gets point, if it does not support then it does not get any point. If one or more than one product supports a specific feature then the total weight of that feature is divided equally between those products, which support that specific feature. If there are two products supporting a specific feature then total weight is divided into two, if just one product supports a specific feature then it gets the full weight of that specific feature- If none of the products has the specific feature then none of the products gets point. The reason for this is that if none of the products has the specific feature then none of them should have competitive advantage against another.

## *3.4 Quantitative Approach for Assessment*

### 3.4.1 Quantitative Approach to Find the Weights of the Determinants

PCM software was used to convert the data coming from focus customer group survey into weights. —except for "Saving" items and "Service Reliability" items because to perform PCM there should be at least three variables compared—Below, you can find the relative weights of each determinant in each level (Tables 2, 3, 4, 5, 6).

**Table 2** Major determinants

| Major determinants | |
|---|---|
| Cost | 0.26 |
| Savings | 0.23 |
| Ease of use | 0.17 |
| Service reliability | 0.15 |
| Additional features | 0.19 |
| Inconsistency | 0.053 |

**Table 3** Sub determinants-Cost

| "Cost" Items | |
|---|---|
| Installation cost | 0.28 |
| Product cost | 0.34 |
| Maintenance cost | 0.38 |
| Inconsistency | 0.057 |

**Table 4** Sub determinants-savings

| "Savings" Items | |
|---|---|
| Energy efficiency | 0.56 |
| Demand response savings | 0.44 |

**Table 5** Sub determinants-ease of use items

| "Ease of use" Items | |
|---|---|
| Ease of installation | 0.33 |
| Interface | 0.35 |
| Personalization | 0.32 |
| Inconsistency | 0.101 |

**Table 6** Sub determinants-service reliability

| "Service reliability" Items | Mean |
|---|---|
| Security | 0.50 |
| Connection availability | 0.50 |

Relative score was divided according to each interface type's average score coming from focus customer group survey. This procedure is the same for the connection types under "Connection Availability" and the features under "Additional Features", too. Below you can see the scores of each interface type, connection type and feature (Tables 7, 8, 9).

**Table 7** Interface items

| "Interface" Items | Scores |
|---|---|
| Website | 0.30 |
| Cell phone | 0.30 |
| PC | 0.25 |
| Special device | 0.15 |

**Table 8** Connection availability

| "Connection availability" Items | Scores |
|---|---|
| Internet | 0.28 |
| SMS | 0.23 |
| Mobile phone | 0.27 |
| Telephone | 0.23 |

**Table 9** Additional features

| "Additional features" Items | Scores |
|---|---|
| Integration with renewables | 0.09 |
| Fire control | 0.07 |
| Light control | 0.10 |
| Phone control | 0.05 |
| Integration with water control | 0.11 |
| Security control | 0.12 |
| Mode control | 0.06 |
| Gas leakage control | 0.12 |
| PC control | 0.07 |
| In home display | 0.11 |
| Integration with appliances | 0.10 |

To find the overall weights of each determinant multiplication of relative weights was used accordingly. For example; to find the overall weight of "Installation Cost" relative weight of "Installation Cost" was multiplied with relative weight of "Cost". Another example for finding overall weight of "Light Control" feature relative weight of "Light Control" was multiplied with relative weight of "Feature". Below you can see relative and overall weights of each determinant used in the model (Table 10).

**Table 10** Total results

| Items | Relative weights | | Overall weights |
|---|---|---|---|
| Installation cost | 28 % | | 7.3 % |
| Maintenance cost | 38 % | | 9.9 % |
| product cost | 34 % | | 8.8 % |
| *Cost* | 26 % | Sum | 26 |

(continued)

**Table 10** (continued)

| Items | Relative weights | | Overall weights |
|---|---|---|---|
| Energy efficiency | 56 % | | 12.9 % |
| Demand response saving | 44 % | | 10.1 % |
| *Savings* | 23 % | Sum | 23 |
| Interface | Website | 30 % | 1.8 % |
| | Cell phone | 30 % | 1.8 % |
| | Special device | 15 % | 0.9 % |
| | PC | 25 % | 1.5 % |
| | Sum | | 6.0 % |
| Interface | 35 % | | 6.0 % |
| Personalization | 32 % | | 5.4 % |
| Ease of installation | 33 % | | 5.6 % |
| *Ease of use* | 17 % | Sum | 17 |
| Connection availability | Internet | 28 % | 2.1 % |
| | SMS | 23 % | 1.7 % |
| | Mobile phone | 26 % | 2.0 % |
| | Telephone | 23 % | 1.7 % |
| | Sum | | 7.5 % |
| Connection availability | 50 % | | 7.5 % |
| Security | 50 % | | 7.5 % |
| *Reliability* | 15 % | Sum | 15 |
| Integration with water control | | 11 % | 2.0 % |
| Light control | | 10 % | 1.9 % |
| Phone control | | 5 % | 0.9 % |
| PC control | | 7 % | 1.4 % |
| In home display | | 11 % | 2.1 % |
| Integration with appliances | | 10 % | 1.9 % |
| Integration with Renewables | | 9 % | 1.8 % |
| Fire control | | 7 % | 1.4 % |
| Security control | | 12 % | 2.2 % |
| Mode control | | 6 % | 1.2 % |
| Gas leakage control | | 12 % | 2.2 % |
| *Features* | 19 % | Sum | 19 |
| Total | | | 100 |

### 3.4.2 Quantitative Approach to Find the Desirability of the Products

To evaluate the focus product group a survey was conducted to expert group. As stated in previous sections experts compared the products in terms of “Installation Cost”, “Product Cost”, “Maintenance Cost”, “Energy Efficiency”, “Demand Response Savings”, and “Ease of Installation” by using pair wise comparison technique. Refer to Appendix: Focus Customer Group Survey and Expert Evaluation Survey. Below you can see the relative weights of each product in specific items.

After obtaining both relative importance of the determinants and performance scores from each product, each product's desirability on percentage basis is calculated. Due to large number of assessment variables, each product's score will be presented with respect to each determinant. It is expected that this feature of the model will be helpful in comparing competitive advantage of ABC's product with competing alternatives. Proposed approach to combine two sets of data coming from customers and experts divide customer desire points between products according to each of the product's performance scores. For example; overall weight of "Installation Cost" is 7.3 % in the whole model. To divide this weight between products, experts' evaluation is taken into consideration. 7.3 % is divided between products according to their relative weights; 22 % of 7.3 is accounted to ABC, 9 % of 7.3 is accounted to Proliphix etc. This approach is followed for "Installation Cost", "Maintaining Cost", "Product Cost", "Energy Efficiency", "Demand Response Savings", "and Ease of Installation" as well.

For other items such as; "Personalization", interface types under "Interface", connection types under "Connection Availability" and features under "Additional Features" a different approach is used. As stated in previous sections, binary variables are used depending on whether a product supports the specific feature or not. Points from each item are divided equally among the products that support the specified feature. In case none of the products supported a specific feature, none of the products receive any points. Thus, summation of each product's desirability is not equal to 100. It is 96.3 as none of the products support SMS type connection—its overall weight is 1.7—and Integration with Water Control feature-its overall weight is 2.

### 3.4.3 Best Practice, Veracity of Data and Methods

Firstly, as survey method was used to gather information, data used in the study rely on subjective ideas. As individuals have their own experience the responses may be based on personal bias. This situation brings weaknesses with itself. Also, 22 responses were received which is very limited amount of data in terms of measuring the market trend and preventing personal bias from being significant on the results.

Apart from personal bias it should also be mentioned that there is significant amount of inconsistency associated with the customer focus group. As seen below in the table amount of inconsistency is worth considering as it is greater than 0.1 [17]. Accordingly, as seen from the table below reliability of the responses from "Ease of Use" cannot satisfy the threshold value. Reason behind this situation may be lack of information about each item. If customers were given enough information about the importance of each item they might have made better comparison.

Another important aspect to mention is the judgment quantification methods used. By preferring scoring method to pair wise comparison method, aim was to cut the amount of time and effort spent on filling the survey. However, this situation might have led missing some of the advantages of pair wise comparison over scoring method. One of the weak points is the division of weights equally between the products that support a specific feature. For example, if weights that each product gets from "Interface" is examined it will be realized that Venstar has the greater desirability although it can only support cell phone interface. Please see Table 11. On the other hand, although ABC, Homeseer and Ecobee can support PC, special device and website interfaces their desirability score are less than Venstar's. This issue could be fixed by not dividing the points between products and just giving the whole points or giving the whole point to a product provided that it can also support all other features which are used by the competitor products (Tables 12, 13).

**Table 11** Product evaluation

| Product evaluation | Installation cost | Maintenance cost | Product cost | Demand response savings | Energy efficiency | Ease of installation |
|---|---|---|---|---|---|---|
| ABC | 0.22 | 0.19 | 0.15 | 0.27 | 0.23 | 0.27 |
| Proliphix | 0.09 | 0.19 | 0.14 | 0.19 | 0.19 | 0.10 |
| Homeseer | 0.21 | 0.20 | 0.21 | 0.17 | 0.21 | 0.19 |
| Venstar | 0.24 | 0.23 | 0.34 | 0.17 | 0.15 | 0.24 |
| Ecobee | 0.24 | 0.19 | 0.16 | 0.20 | 0.22 | 0.20 |
| Inconsistency | 0.035 | 0.016 | 0.056 | 0.037 | 0.034 | 0.049 |

**Table 12** Final analysis

| | | | ABC | | Proliphix | | Homeseer | | Venstar | | Ecobee | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cost* | | Sum | 4.81 | | 3.77 | | 5.36 | | 7.02 | | 5.04 | |
| | Installation cost | | 1.61 | | 0.66 | | 1.53 | | 1.75 | | 1.75 | |
| | Maintenance cost | | 1.88 | | 1.88 | | 1.98 | | 2.28 | | 1.88 | |
| | Product cost | | 1.32 | | 1.23 | | 1.85 | | 2.99 | | 1.41 | |
| *Savings* | | Sum | 5.69 | | 4.37 | | 4.43 | | 3.65 | | 4.86 | |
| | Energy efficiency | | 2.97 | | 2.45 | | 2.71 | | 1.94 | | 2.84 | |
| | Demand response savings | | 2.73 | | 1.92 | | 1.72 | | 1.72 | | 2.02 | |
| *Easy of use* | | Sum | 5.34 | | 1.39 | | 2.19 | | 3.14 | | 4.95 | |
| | Ease of installations | | 1.51 | | 0.56 | | 1.06 | | 1.34 | | 1.12 | |
| | Personalization | | 2.70 | 1 | 0 | – | 0 | – | 0 | – | 2.70 | 1 |
| | Interface | | 1.13 | | 0383 | | 1.13 | | 1.80 | | 1.13 | |
| | | Website | 0.45 | 1 | 0.45 | 1 | 0.45 | 1 | 0 | – | 0.45 | 1 |
| | | Cell phone | 0 | – | 0 | – | 0 | – | 1.80 | 1 | 0 | – |
| | | Special device | 0.30 | 1 | 0 | – | 0.30 | 1 | 0 | – | 0.30 | 1 |
| | | PC | 0.38 | 1 | 0.38 | 1 | 0.38 | 1 | 0 | – | 0.38 | 1 |
| *System reliability* | | Sum | 4.28 | | 0.53 | | 0.53 | | 3.70 | | 4.28 | |
| | Security | | 3.75 | 1 | 0 | – | 0 | – | 0 | – | 3.75 | 1 |
| | Connection availability | | 0.53 | | 0.53 | | 0.53 | | 3.70 | | 0.53 | |
| | | Internet | 0.53 | 1 | 0.53 | 1 | 0.53 | 1 | 0 | – | 0.53 | 1 |

(continued)

**Table 12** (continued)

| | | ABC | | Proliphix | | Homeseer | | Venstar | | Ecobee | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SMS | 0 | – | 0 | – | 0 | – | 0 | – | 0 | – |
| | Mobile phone | 0 | – | 0 | – | 0 | – | 2.00 | 1 | 0 | – |
| | Telephone | 0 | – | 0 | – | 0 | – | 1.70 | 1 | 0 | – |
| *Additional features* | Sum | 1.50 | | 4.63 | | 2.12 | | 1.82 | | 7.23 | |
| | Integration with water control | 0 | – | 0 | – | 0. | – | 0 | – | 0 | – |
| | Light control | 0 | – | 0.63 | 1 | 0.63 | 1 | 0 | – | 0.63 | 1 |
| | Phone control | 0 | – | 0 | – | 0 | – | 0.90 | 1 | 0 | – |
| | PC control | 0.35 | 1 | 0.35 | 1 | 0.35 | 1 | 0 | – | 0.35 | 1 |
| | In home display | 0.53 | 1 | 0.53 | 1 | 0.53 | 1 | 0 | – | 0.53 | 1 |
| | integration with appliances | 0.38 | 1 | 0.38 | 1 | 0.38 | 1 | 0.38 | 1 | 0.38 | 1 |
| | Integration with renewables | 0 | – | 0 | – | 0 | – | 0 | – | 1.80 | 1 |
| | Fire control | 0 | – | 1.40 | 1 | 0 | – | 0 | – | 0 | – |
| | Security control | 0 | – | 1.10 | 1 | 0 | – | 0 | – | 1.10 | 1 |
| | Mode control | 0.24 | 1 | 0.24 | 1 | 0.24 | 1 | 0.24 | 1 | 0.24 | 1 |
| | Gas leakage control | 0 | – | 0 | – | 0 | – | 0 | – | 2.20 | 1 |
| Total sum | | 21.61 | | 14.68 | | 14.63 | | 19.04 | | 26.35 | |

**Table 13** Ease of use

| "Ease of use" Items | Mean | Max | Min | Std dev |
|---|---|---|---|---|
| Ease of installation | 0.33 | 0.57 | 0.16 | 0.11 |
| Interface | 0.35 | 0.47 | 0.21 | 0.07 |
| Personalization | 0.32 | 0.6 | 0.11 | 0.12 |
| Inconsistency | 0.101 | | | |

It is important to emphasize that one of the gaps that involves in not knowing how customers would react if any of the variables in the model was excluded from the assessment. As stated in the previous section SMS type connection and Integration with Water Control features are not included in any of the products in the field. Accordingly, it is very important to know how people would react to a product, which has these missing features. For example; to what degree weights of "Internet", "Mobile Phone" and "Telephone" would change, if weights of other major or sub determinants change. If this gap is bridged new opportunities or emerging competitors could be analyzed better.

## 4 Consumer Analysis

Enhancing the ability to respond to price signals could benefit not only the consumers who choose to participate actively in electricity markets, but would also help these markets operate more efficiently and satisfactorily [4]. This is the key component for the consumer's selection of products. Though they care about additional features that technology will enable, they overwhelmingly prefer cost benefit that an energy demand system would provide. The value of demand side management to electricity customers has not changed since the mid-1980. DSM is still valuable to the extent it lowers customer's bills, particularly if the measures do not detract from comfort, convenience, or performance [15]. From a consumers point of view one of the largest factors contributing to the purchase of these devices is the cost, and savings. The technology that enables this will also enable other functionality that may be of interest to the consumer.

## *4.1 Smart Thermostat Evaluation*

One of the easiest means of penetration into the demand side management market is to design a thermostat that is responsive to signal or in other words able to communicate with the outside world. Criteria for selecting these devices were based on two characteristics such that ability to control the HVAC system through a programmable thermostat and ability to communicate with the outside world in some manner. All of the products investigated took different approaches to solving the demand side management challenge. So a comparison based on features, cost, and other consumer preferences was used in order to compare the products on a quantitative level.

Prior to beginning the investigation there was much speculation on which product created the most value for the consumer's dollars. It was quickly discovered that a product could be created at relatively low cost and still be competitive with products 4–5 times more expensive. For example the University of California performed a study in which they were able to build a proof of concept communicating thermostat with a bill of material cost of $20 [16]. Based on the consumer response and expert response of product definition the Ecobee unit turned out to have the greatest value to the consumer. This resulted from the very large spread of functionality and methods of interface.

## *4.2 Technology Impact*

Products compared in this study will impact consumers in different ways depending on the technology they used in creating the device. Venstar's phone control capability creates an advantage over the other products by allowing the consumer to interact with the device while driving. On the other hand ABC has an interface that allows the user not only to interact with the device from anywhere in the world, but it also transforms the data collected on the unit and the web and transforms it into information that is relevant to the consumer. Technology is not the hurdle in creating a successful product, it is packaging just enough features for the consumer without adding on additional unwanted functionality that will burden the unit with higher cost.

## 5 Discussion of the Results

This chapter built upon the summary provided by Daim and Iskin [18]. Overall evaluation of the products can be seen below. According to Fig. 2 Ecobee and ABC seem to have the most desirable products in the focus product group. So it could be stated that Ecobee is the strongest competitor of ABC. In the following section, products that are subject to assessment will be compared with respect to each determinant.

Data was analyzed and desirability of each product from each determinant was calculated. To be able to observe the results figures for each determinant was drawn.

From the Fig. 3 below Venstar seems to have the biggest desirability from cost item which is not a surprise because its cost items are lower than its competitors. ABC and Ecobee have the same desirability.

From the Fig. 4 below ABC gets the highest desirability from energy savings. "Ability of Demand Response Savings" seems to be more attractive than Ecobee's, but the difference would not be considered as significant. Also, as seen from the figure it could be said that nearly every product has the same amount of attractiveness in energy efficiency item.

From the Fig. 5 below ABC and Ecobee seem to have the greatest attractiveness when they are compared to others. While personalization and interface features are equal ABC seems to make the difference from its ease to installation. It should further be noted that ratio of Interface in Ease of Use is considerable.

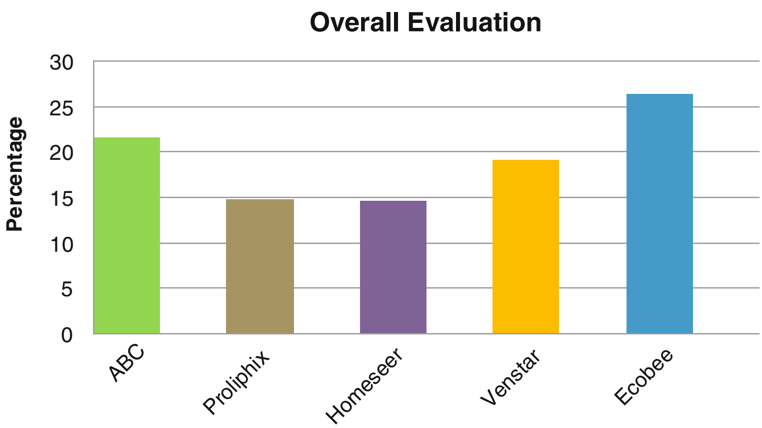


**Fig. 2** Overall evaluation

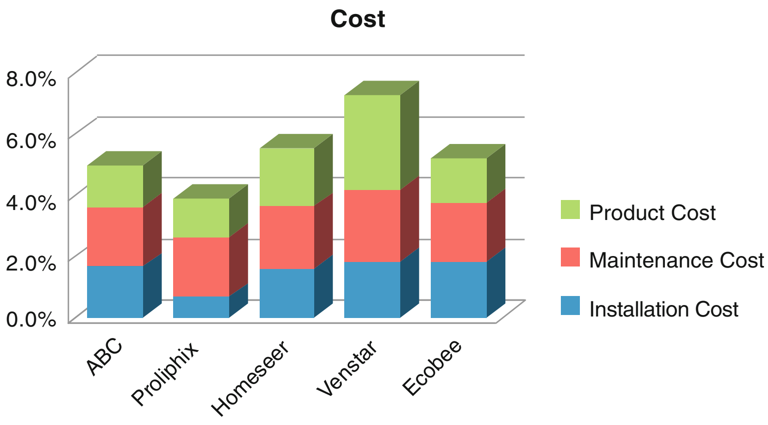


**Fig. 3** Cost comparison

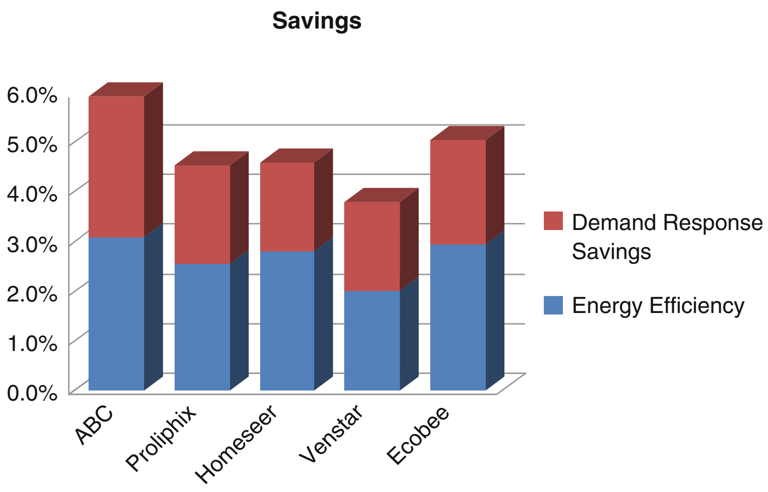


**Fig. 4** Savings comparison

Interface is a sub item under ease of use and from the Fig. 6 below it could be said that Venstar is the only product which supports cell phone interface to its customers whereas ABC and Ecobee focus on providing interfaces through website, PC and special devices. The reason why Venstar has greater desirability than the others is the division of the weights equally between the products which support a specific feature.

From the Fig. 7 below it could be said that ABC and Ecobee are the only products, which support security function, and they have the same desirability. The ratio of connection availability seems to be low when it is considered to whole.

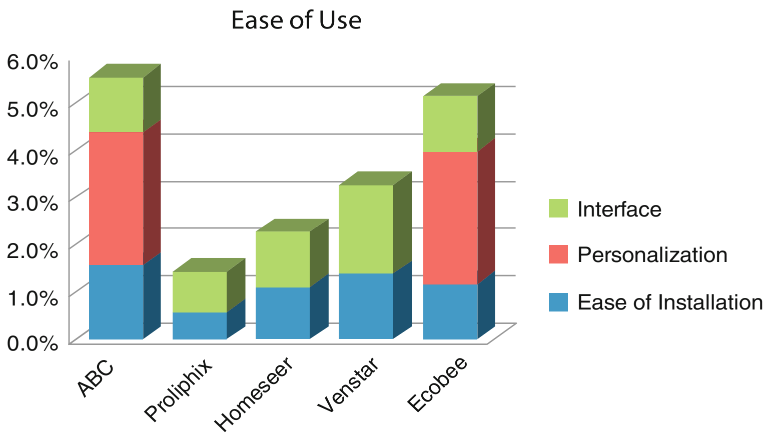


**Fig. 5** Ease of use comparison

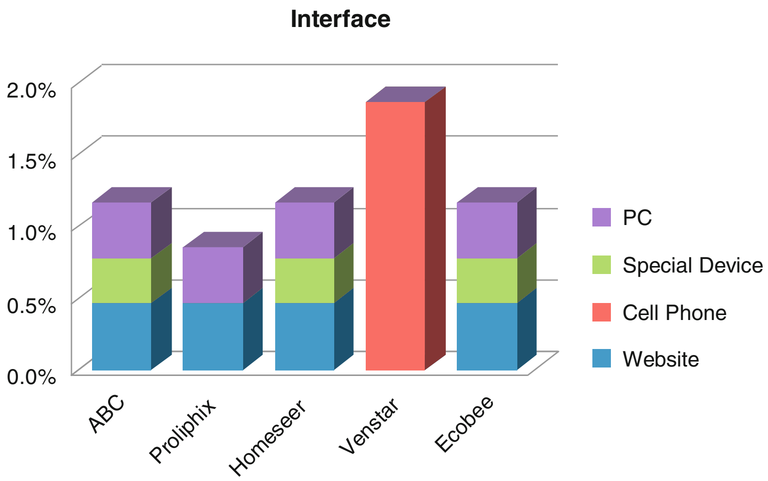


**Fig. 6** Interface comparison

From the Fig. 8 below unsurprisingly Venstar's desirability is quite big as it has two ways to communicate within the system where as all other products use internet as its communication way. The reason why Venstar has greater desirability than the others is the division of the weights equally between the products which support a specific feature. ABC and Ecobee have the same amount of desirability in this item.

From the Fig. 9 below, additional feature profile of each product can be observed. Accordingly, Proliphix and Ecobee seem to have the greatest desirability whereas ABC's score is quite low. Reason behind this is the competitive

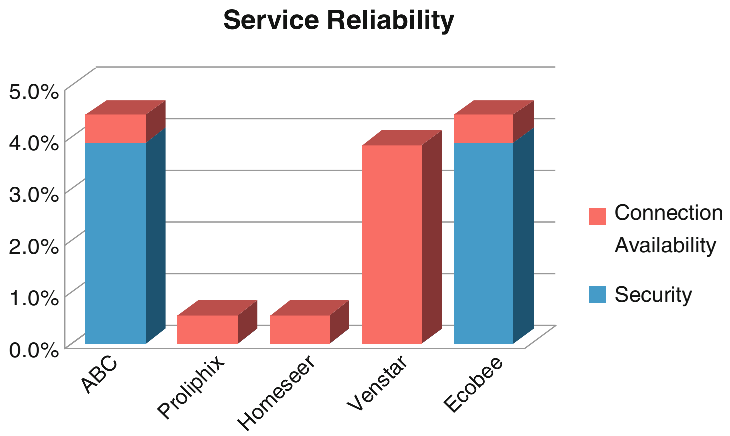


**Fig. 7** Service reliability comparison

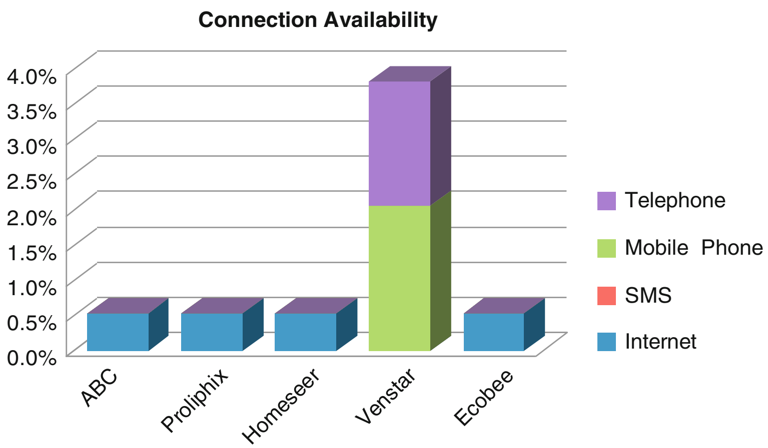


**Fig. 8** Connection availability comparison

advantage that the domination of ABC and Ecobee on some of the additional features. For example; Gas leakage control and integration with renewables can only be supported by Ecobee and Proliphix is the only product which can support fire control feature. The reason why ABC has low desirability in this item is that it just focuses on the features which can also be supported by the other products. Apart from additional features ABC and Ecobee do not show significant difference and as a result their desirability is the same, but Ecobee makes the difference through additional features and this causes Ecobee to be more popular. Features that are not included in any of the focus products can be observed from the figure above. It should be noted that their weights are quite considerable (Fig. 10).

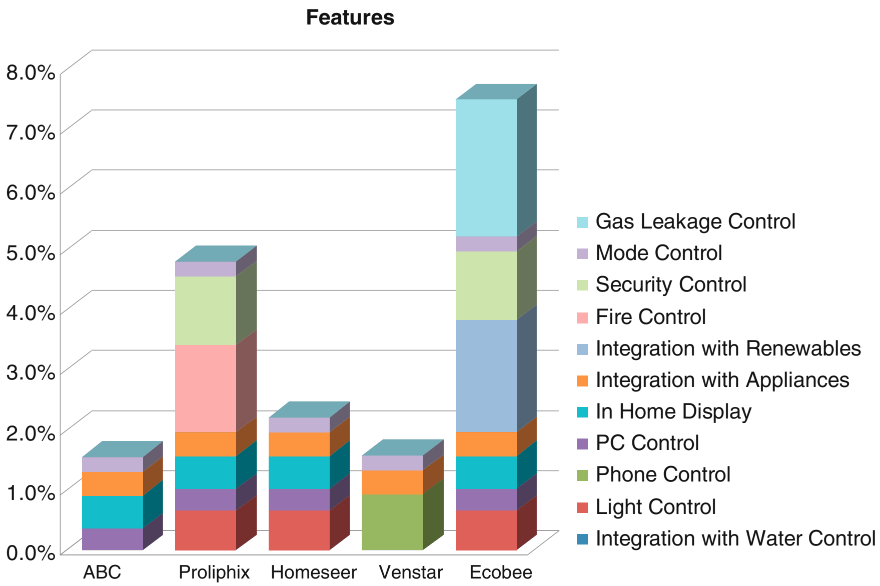


**Fig. 9** Feature comparison

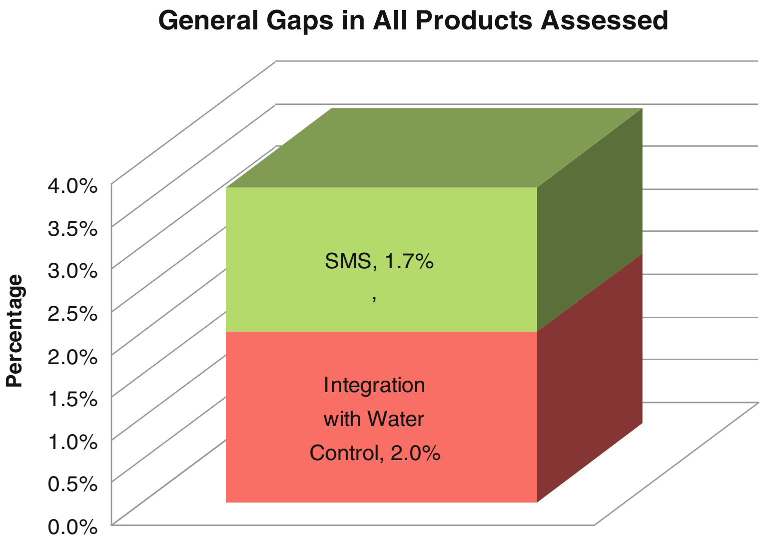


**Fig. 10** General gaps in all products assessed

# 6 Recommendations for ABC

As seen in the Fig. 11 below, surveyed customers are concerned about additional features as much as low cost and savings potential at a higher level. A similar pattern can also be observed at the sub-determinants level, please refer to Fig. 12 below for further detail (Fig. 12).

According to results it can be stated that ABC has an advantage in providing "Energy Savings" and "Demand Response Savings". The "Cost" could also be considered as competitive as its desirability is not too low. In terms of "Ease of Use" ABC ranks among the best of the products assessed. It may be worth their while to continue to develop better interfaces to make it as simple and intuitive as possible. Investing in a simple, easily understandable and accessible user guide will also make it easier for customers to pick and recommend their products. If ABC can improve its system to support cell phone interface it could provide competitive advantage as none of the products except Venstar provides this feature. Considering "Service Reliability", adding new communication ways such as; telephone, mobile phone and SMS would help ABC create competitive advantage against its competitors. One of the most important points for ABC is the additional features that it can provide. As mentioned in previous sections ABC is one of the least desirable products in this section. Adding new features will dramatically

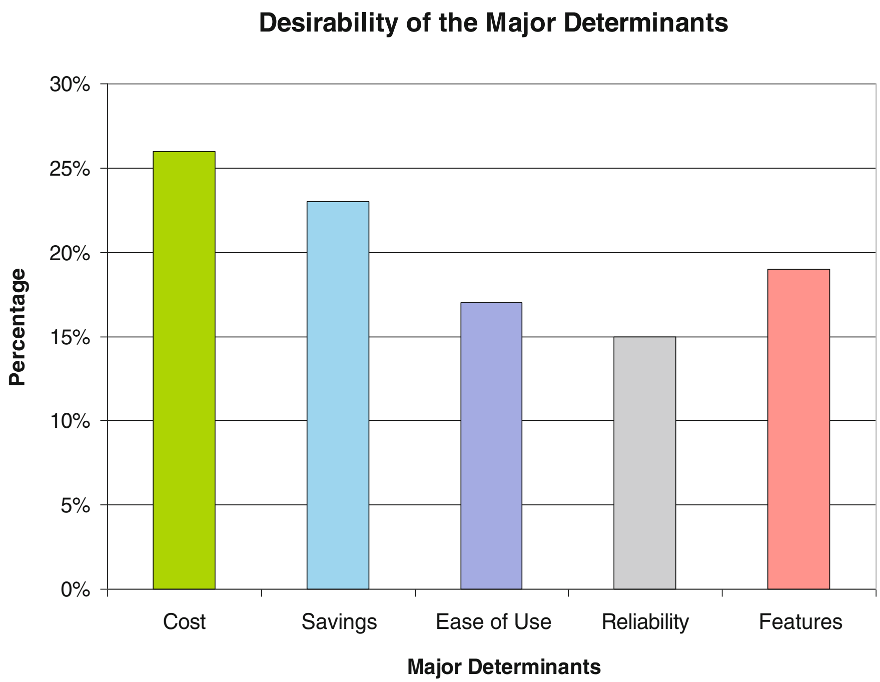


**Fig. 11** Desirability of major determinants

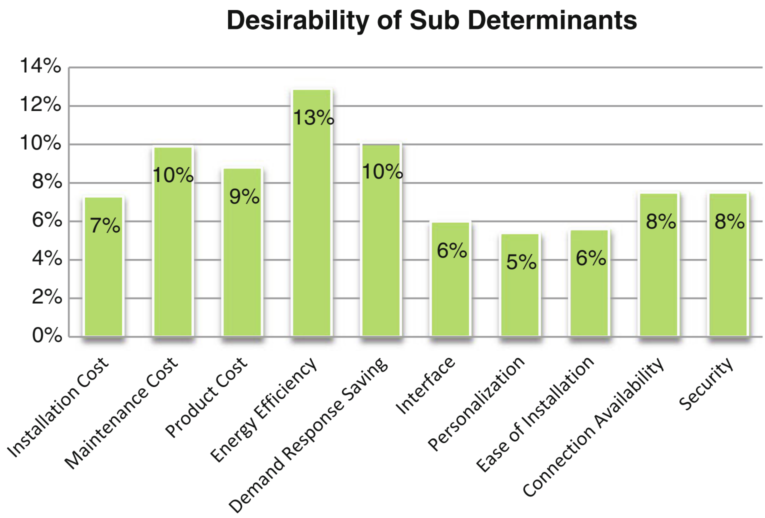


**Fig. 12** Desirability of sub determinants

increase customer perception in positive way especially "Gas Leakage Control" and "Integration with Renewables" By not only adding missing features but also adding the features of SMS connection availability and integration with water control, ABC could ease its market acceptance. To achieve this end, ABC could consider seeking partnerships with OEM's and other technology providers to ensure that their product is fully compatible with, and fully supports, other technology modules that may add value to ABC products. Some R&D effort will be needed to add new features as mentioned above.

## 7 Conclusion

Many interesting results were derived from analysis of the survey data. The survey identified some strengths and weaknesses of ABC that make sense. It is believed that ABC is one of the stronger competitors in the market, but must focus much effort on minimizing cost. It is important to note that bias is added to survey based on the way a question is phrased, and it has been identified that this as an area for future work. Also a small sample size of participants can create a lopsided impression of the devices and functionality desirability. A larger sample size, with better-defined questions, using the analysis we developed, could help lower and risk and focus ABC in their future steps.

### 7.1 Future Work

It is very important to predict customer desirability trend when there is potential for market to have a new feature emerging or an emerging product with existing features. Future studies could revise focus customer group surveys by adding or omitting some of the features and conduct a similar assessment. It would be possible to observe how the weights of customer desire moves between determinants. This knowledge would help managers to give decisions about product features. Organizations could save capital by not investing every emerging R&D projects but could save a lot by investing capital on the features, which are to provide competitive advantage.

**Acknowledgments** We would like to thank Brian Muchilwa, Nathan Hadlock, Bing Wang, and Mike Hoffman for their valuable contributions to successful completion of this study.

## A.1 Appendix

### A.1.1 Explanations of Additional Features

*Integration with water control*: Ability to control water consumption within the residential area for example; measuring the moisture in the earth and making decision to water the grass or not.
*Integration with home appliances*: Ability to control the energy consumption of the home appliances within the residential areas for example; closing television when it is idle.
*Light control*: Ability to manage lights in the house for example turning off the lights when there is no one in the room or turning on the lights when there is someone in the room.
*Fire control*: Ability to control fire alarm system.
*Phone control*: Ability to communicate with phone.
*Security control*: Ability to communicate with alarm system.
*Mode control*: Ability to set the device for specific conditions for example setting it to holiday mode when you are on vocation.
*Gas leakage control*: Ability to detect gas leakage.
*PC control*: Ability to communicate with PC and allowing users to reach their devices through their PC.
*In home display control*: Ability to manage and communicate with video or audio systems within the residential places.

### A.1.2 Focus Customer Group Survey

1. If you were to buy a smart grid device for your house which of these additional "Features" would be important to you? Please, rate the features on scale of 1: Least important-10: Most important

| |
|---|
| Integration with water control |
| Light control |
| Phone control |
| PC control |
| In home display |
| Integration with appliances |
| Integration with renewables |
| Fire control |
| Security control |
| Mode control |
| Gas leakage control |

2. If you were to buy a smart grid device for your house which of these "Interfaces" would be suitable to you? Please, rate the interfaces on scale of 1: Least suitable-10: Most suitable

| |
|---|
| Website |
| Cell phone |
| Special device |
| PC |

3. If you were to buy a smart grid device for your house which of these "Connections" types would be suitable to you? Please, rate the connection types on scale of 1: Least suitable-10: Most suitable

| |
|---|
| Internet |
| SMS |
| Mobile phone |
| Telephone |

4. If you were to buy a smart grid device for your house which of these "Ease of Use" items would be important to you? Please, rate the percentages according to information given.

| | |
|---|---|
| Ease of installation | Interface |
| Ease of installation | Personalization |
| Personalization | Interface |

5. If you were to buy a smart grid device for your house which of these “Savings” items would be important to you? Please, rate the percentages according to information given.

| | |
|---|---|
| Energy efficiency | Demand response savings |

6. If you were to buy a smart grid device for your house which of these “Reliability” items would be important to you? Please, rate the percentages according to information given.

| | |
|---|---|
| Security | Connection availability |

7. If you were to buy a smart grid device for your house which of these “Cost” items would be important to you? Please, rate the percentages according to information given.

| | |
|---|---|
| Installation cost | Product cost |
| Installation cost | Maintenance cost |
| Product cost | Maintenance cost |

8. Please, rate the percentage of items below in terms of their importance according to the information given.

| | |
|---|---|
| Cost | Savings |
| Cost | Ease of use |
| Cost | Reliability |
| Cost | Features |
| Savings | Ease of use |
| Savings | System reliability |
| Savings | Features |
| Ease of use | Reliability |
| Ease of use | Features |
| Reliability | Features |

### A.1.3 Expert Evaluation Survey

9. Please, rate the percentages of buying specific product according to the information given.

| Installation cost | | Maintaining cost | |
|---|---|---|---|
| ABC | Proliphix | ABC | Proliphix |
| ABC | Homeseer | ABC | Homeseer |
| ABC | Venstar | ABC | Venstar |
| ABC | Ecobee | ABC | Ecobee |
| Proliphix | Homeseer | Proliphix | Homeseer |
| Proliphix | Venstar | Proliphix | Venstar |
| Proliphix | Ecobee | Proliphix | Ecobee |
| Homeseer | Venstar | Homeseer | Venstar |
| Homeseer | Ecobee | Homeseer | Ecobee |
| Venstar | Ecobee | Venstar | Ecobee |

| Product cost | | Energy efficiency | |
|---|---|---|---|
| ABC | Proliphix | ABC | Proliphix |
| ABC | Homeseer | ABC | Homeseer |
| ABC | Venstar | ABC | Venstar |
| ABC | Ecobee | ABC | Ecobee |
| Proliphix | Homeseer | Proliphix | Homeseer |
| Proliphix | Venstar | Proliphix | Venstar |
| Proliphix | Ecobee | Proliphix | Ecobee |
| Homeseer | Venstar | Homeseer | Venstar |
| Homeseer | Ecobee | Homeseer | Ecobee |
| Venstar | Ecobee | Venstar | Ecobee |

| Demand response saving | | Ease of installation | |
|---|---|---|---|
| ABC | Proliphix | ABC | Proliphix |
| ABC | Homeseer | ABC | Homeseer |
| ABC | Venstar | ABC | Venstar |
| ABC | Ecobee | ABC | Ecobee |
| Proliphix | Homeseer | Proliphix | Homeseer |
| Proliphix | Venstar | Proliphix | Venstar |
| Proliphix | Ecobee | Proliphix | Ecobee |
| Homeseer | Venstar | Homeseer | Venstar |
| Homeseer | Ecobee | Homeseer | Ecobee |
| Venstar | Ecobee | Venstar | Ecobee |

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# Solar Lanterns: Technology Adoption Model for Indian Villages

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**Abstract** Photovoltaic technology is one of the most promising ways to generate electricity in a decentralized manner, especially for lighting and meeting small electricity needs in un-electrified households and unmanned locations. In India lack of electricity infrastructure is one of the main hurdles in the development of rural India. In most of the rural India grid based power distribution is not possible due to high costs, kerosene is the only source of energy in some villages, and so off grid solar power sources are necessary for providing electricity. In this paper, we study the drivers and barriers for the adoption of solar lanterns in rural India, conduct and economic analysis and present a framework for solar lanterns adaption. The model involves four major players, technology manufacturers, NGOs and village leaders, lending institutions, and central and local governments. In the proposed framework post offices in the villages are operate as a single point of contact for sales, financing, payments and maintenance.

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## 1 Introduction

India has made tremendous economic progress in the last decade; the rate of growth has been more than 5 %. But this economic progress has not been consistent between cities and villages. Seventy percent of the Indian population lives in villages and a large number of villages are without electricity. There have been numerous Government run programs in the last five decades to electricity villages. The Indian Government hopes to complete electrification of all villages by 2012. But distribution of electric power in villages remains a constant challenge. In addition to coal and nuclear based power, efforts are being made by a large number of Non Profit Organizations to bring Solar Power to rural India.

> We will pool all our scientific, technical and managerial talents, with financial sources, to develop solar energy as a source of abundant energy to power our economy and to transform the lives of our people—Prime Minister of India [1].

This paper looks at the 'Decentralized Model of Power Generation' using photovoltaic panels and the value drivers for moving to Solar Energy for supplying power to homes in rural areas of India. As fact, energy is the main requirement for economic progress of an area. Solar technology can help the rural people achieve economic growth and leapfrog into the twenty-first century. In this paper, we look into how Solar Lanterns can satisfy the lighting needs of Indian villages—leading to improvements in productivity and quality of life.

**Problem Statement**

The problem of electricity supply is more acute for Indian villages. Around 80,000 of more than 800,000 villages in India do not yet have any electric supply; 78 million rural households are without electricity. As per the new definition, a village would be declared as electrified, if:

- Basic infrastructure, such as distribution transformer and distribution lines, is provided in the inhabited locality.
- Electricity is provided to public places like schools, health centers, dispensaries, community centers etc.
- The number of households electrified should be at least 10 % of the total number of households in the village [2].

Besides food, shelter, clothing and employment, the next priority in Indian Villages is the affordable energy supply for cooking and lighting. Life in rural India is miserable due to non-availability of electricity. Several states in India claim that 40, 50 or even 100 % of villages have been electrified. But supply of electricity to villages that have been electrified is not for more than 3–4 h per day. It is a big hindrance in development. Globalization is not going to make much difference to rural life until and unless electricity is supplied uninterruptedly 10–12 h per days to these villages.

"**Lack of electricity is a core cause of malnutrition, starvation, illiteracy and extreme poverty around the world.**" Moreover, lack of reliable, affordable and clean energy disproportionately harms the health, education and productivity of women and children—who make up the majority of the poor in any community. Providing electricity to poor communities can reduce the amount of time needed for cooking, collecting water, and other activities. Using solar power can further reduce environmental and health threats by replacing the noxious fumes of kerosene lanterns and cook stoves with a clean energy source [3].

Solar energy can be a solution to the energy problem of Indian Villages. We look at a decentralized model of Energy (you need not to be only a consumer but you can be a producer also). Real challenge is how to give electric supply in 10 days instead of 10 years.

# 2 Literature Review

## *2.1 Current Energy Scenario*

India has a share of approximately 16 % of world's population. The country occupies 2 % of the world's land mass and currently generating 2 % of the global electricity. Most of this electricity is generated using low grade coal. At present, Non Conventional energy sources such as solar, wind and biomass have more than 3000 MW of capacity [4] which is around 3 % of the total installed power generating capacity of 103,000 MW [5].

India is heavily dependent on coal and foreign oil for its energy needs and this phenomenon is likely to continue until renewable energy technology becomes commercially viable in the country [2].

## *2.2 India's National Solar Mission*

The Union Government has finalized the draft for the National Solar Mission. It aims to make India a global leader in solar energy and envisages an installed solar generation capacity of 20,000 MW by 2020, 100,000 MW by 2030 and of 200,000 MW by 2050. The total expected funding from the government for the 30-year period is projected about $18 billion to $22 billion. Implementation will be in three phases [1].

- First phase will try to achieve rapid scaling up to reduce (unit) costs. This phase will spur domestic manufacturing.
- Second phase will focus on the commercial deployment of solar thermal power plants.
- Third phase will make efforts to achieve tariff parity with conventional grid power.

India has proposed that by 2012, 10 % of annual additions to power generation would be from renewable energy [6].

India is one of the few countries that have a dedicated ministry for the promotion of non conventional energy—the Ministry of New and Renewable Energy (MNRE). MNRE is the nodal Ministry of the Government of India for all matters relating to new and renewable energy. The broad aim of the Ministry is to develop and deploy new and renewable energy for supplementing the energy requirements of the country. MNRE has setup a target of 10 % power generation from renewable. MNRE is trying to electrify as many villages as possible with the solar PV technology. The Indian Renewable Energy Development Agency (IREDA) has a fund to help companies offering affordable credit for the purchase of PV systems [5].

The Indian Renewable Energy Development Agency Ltd. (IREDA) was established in 1987 as a Public Sector Non-Banking Company under the Ministry of Non-Conventional Energy Sources (MNES) with the objective of providing loans for new and renewable sources of energy [7]. It has played a key role in the development of renewable energy in India. During 2004, IREDA has sanctioned loans to the tune of $570 million and disbursed $350 million against the annual targets of $900 million and $630 million respectively. The loans were sanctioned for the establishment of about 152.80 MW of installed capacity of power generation and 584.64 metric tons coal replacement projects from renewable sources. The cumulative sanctions and disbursements as on 31st December 2004 were $1.1 billion and $0.6 billion respectively [8]. Table 1

## 3 Technology Assessment

Researchers estimate that the sun produces enough energy in a single second to meet the needs of all humanity for 2000 years. “The surface of the Earth receives an amount of solar energy equivalent to roughly 10,000 times the world energy demand,” wrote Erik Lysen in the January 2003 issue of Renewable Energy World magazine [9].

**Table 1** Installed capacity of energy sources as on March 31, 2005 [27]

| Installed capacity | Million watts |
|---|---|
| Coal | 67791 |
| Diesel | 1201 |
| Gas | 11910 |
| Sub total | 80902 |
| Solar and renewable energy | 3811 |
| Nuclear | 2770 |
| Hydro | 30936 |
| Grand total | 118419 |

**Annual Solar Insulation**

India lies in the sunniest regions of the world. The highest annual radiation energy is received in parts of Rajasthan state like the Thar Desert. Most of the places in India normally get sun for all 12 months. Even during the rainy season, sunlight is available for few hours daily. With approximately 300 clear sunny days in a year, India's theoretical solar power reception, just on its land area, is about 5000 trillion kWh/yr (5 PWh/year (i.e. = ~600 TW). The daily average solar energy power over India varies from 4 to 7 kWh/m2 with about 2,300–3,200 sunshine hours per year, depending upon location. This is far more than current total energy consumption. For example, even assuming 10 % conversion efficiency for PV modules, it will still be thousand times greater than the likely electricity demand in India by the year 2015 [10].

## 4 Technology Overview

Solar technology is currently divided into two categories—Thermal and Photovoltaic. Thermal solar power uses the heat of the sun, and photovoltaic, or PV, is the technology that converts its light directly into electricity [6]. Solar Photovoltaic (PV) technology enables direct conversion of sunlight into electricity. Photovoltaic cells, commonly known as solar cells, are used to convert light (photon) into electricity. Most of the commercially available solar cells are made from high purity silicon wafers. Solar cells can also be made from several materials such as silicon thin films both multi crystalline and amorphous, cadmium telluride (CdTe), copper indium diselenide (CIS), gallium arsenide (GaAs) etc.

The photovoltaic technology is one of the most promising ways to generate electricity in a decentralized manner at the point of use for providing electricity, especially for lighting and meeting small electricity needs especially in un-electrified households and unmanned locations. During the last three decades significant efforts have gone into the development and evolution of solar photovoltaic technology and deployment of PV systems for a large number of applications. In the last 20 years of the twentieth century photovoltaic panel efficiencies doubled [11].

### *4.1 How a Solar Lanterns works*

A solar lantern is a simple lantern, which uses a small PV cell to generate electricity instead of using only batteries or using kerosene as the source of the energy. The solar module can be charged during the day from the regular sunlight and plugged back into the solar lantern during the night.

Product features of a typical Solar Lantern are described below [12]:

- Light and portable design
- Flexible usage and multiple-setting handles
- Tough and sturdy design
- Weather resistant to sun and rain
- Smart solar indicator for charge intensity
- Easily-replaceable, rechargeable, high-performance Ni-Mh battery
- High-efficiency integrated polycrystalline solar panel.

In this paper, we study two models for Solar Lantern and compare their features and cost.

**Model: Kiran S10**

An all-in-one solar light, Kiran S10 is the perfect replacement for kerosene lanterns in the home, workplace, or on the go. High-quality and affordable, this model features an upgraded battery and an LED lamp, resulting in better, more reliable performance at the same price. It provides up to 8 h of light on a full battery and uses highly efficient LEDs. It provides 360-degree space lighting for the home, workplace, or while traveling. It also serves as a task lamp for studying, working, or cooking. A highly efficient solar panel is conveniently integrated into every Kiran S10 to make solar charging as easy as possible. It is designed to be extremely user-friendly and flexible. It has no detachable parts and includes an integrated solar panel that makes recharging simple and easy. The product shape, portability, and multiple-setting handle give the customer many options for use. It can be carried, hung from the wall or ceiling, or placed on any surface to effectively illuminate the surrounding area [13].

**Nova S250**

Nova S250 is a dual purpose solar light and mobile charger. Its bright white light illuminates a room as much as a 3–5 Watt CFL lamp, and is up to five times more energy efficient. It provides up to 10 times more light than a kerosene lantern. It also charges the most popular mobile phones on the market. It keeps personal mobile phones fully charged even when AC power is unavailable or inconvenient.

S250 provides a bright white light projected at a wide angle; it can effectively illuminate an entire room. It uses a highly efficient LED, designed to last more than 50,000 h with no appreciable performance degradation. S250 features four different brightness settings, providing up to 12 h of bright light (and up to 100 h on the bed light setting). In addition, the illuminated on/off button allows for easy location of the lamp even in the dark. d.light S250 is encased in a sturdy housing unit that is water resistant and protects the interior from dust and large insects. Weighing only 350 g, it comes with an ergonomically designed handle and top strap, providing users with the maximum flexibility for use in. On a full day's charge, S250 can charge your mobile phone to 80 % of its full battery capacity in as little as 1 h (Table 2).

**Table 2** Economic analysis of the solar lantern

| Parameter | | Basic solar lantern | Solar lantern with cell phone charger |
|---|---|---|---|
| Product | Kerosene lantern | Kiran S10 | Nova S250 |
| Price of lantern | n/a | 485 | 1495 |
| Monthly expenses for consumable (4 l kerosene at Rs. 22/l) | 88 | 0 | 0 |
| Government subsidy @ 10 % | 0 | 49 | 150 |
| Upfront investment = P (present value) | n/a | 437 | 1346 |
| Interest per month = i | n/a | 1 % | 1 % |
| Number of months (payments) = N | n/a | 12 | 12 |
| Monthly investment = A | n/a | 40 | 120 |

Formula for these calculations is given below (Sullivan 2003)

P = A (P/A, i %, N) P = A (11.2551)

**Goal**:

(1) After 1 year villagers own the lantern free and clear (2) Villagers are replacing two lanterns—one for home and one for shop (3) Kiran S10 is for Home and Nova S 250 is for Shop (4)

**Comparison**:

Total Monthly Payment for 2 Lamps = Rs. 176

Monthly Kerosene cost for 2 lamps = Rs. 160

**Information/Assumptions:**

(1) All Costs are in Indian Rupees and 1 US Dollar = Rs. 45 [14]. (2) Villagers already own the kerosene Lantern and it has no resale value (3) Usage Time of a Lamp is for 3 h in the evening (Table 3).

## 5 Market Drivers

In India, Solar PV mode of electrification started in 1998 after a system on a trial basis was commissioned in Kamalpur village in 1996 [15]. Some of the market drivers for solar power for Indian villages are as follows:

- **Ease of operation**: Solar PVs are simple to use and do not require a lot of training, making the adaption of this technology easy
- **Simple to maintain**: Solar PV is simple and easy to maintain as there are no moving parts and the design is modular.
- **Improve productivity, safety and life quality for villagers**: In remote industrial applications, solar PV can be a cheaper alternative to diesel power generation, especially to power small electrical loads of up to hundreds of Watts. Kerosene is the only source of energy in some villages. Sometimes, villagers have to walk couple of miles just to fetch a few liters of kerosene. Small shopkeepers cannot keep their shops open in the night due to lack of

**Table 3** Potential of Indian states for solar lantern consumption [28]

| State/group of states/territory | Estimated number of rural households | Percentage of rural households using kerosene | Average monthly per capita expenditure (MPCE) | Number of households using kerosene for lighting |
|---|---|---|---|---|
| Orissa | 7264000 | 69.40 | 380 | 5041216 |
| Chhattisgarh | 3554300 | 20.60 | 422 | 732185.8 |
| Tripura | 646900 | 45.90 | 452 | 296927.1 |
| Madhya Pradesh | 9626500 | 32.60 | 469 | 3138239 |
| Andhra Pradesh | 14813700 | 13.30 | 493 | 1970222.1 |
| Jharkhand | 3972300 | 62.20 | 495 | 2470770.6 |
| Bihar | 14963200 | 88.20 | 532 | 13197542.4 |
| North-eastern states | 1807000 | 26.80 | 545 | 484276 |
| West bengal | 14335000 | 62.10 | 552 | 8902035 |
| Gujarat | 7127700 | 15.70 | 565 | 1119048.9 |
| Karnataka | 7602200 | 11.60 | 572 | 881855.2 |
| Assam | 5786600 | 67.00 | 573 | 3877022 |
| Uttar Pradesh | 24563100 | 71.80 | 584 | 17636305.8 |
| Manipur | 29990 | 12.80 | 589 | 3838.72 |
| Haryana | 311100 | 3.50 | 633 | 10888.5 |
| Tamil Nadu | 9713400 | 9.60 | 651 | 932486.4 |
| Rajasthan | 7687500 | 44.80 | 660 | 3444000 |
| Maharashtra | 11945900 | 27.20 | 666 | 3249284.8 |
| Meghalaya | 382000 | 25.40 | 670 | 97028 |
| Punjab | 3451200 | 11.00 | 682 | 379632 |
| Arunachal Pradesh | 135900 | 16.80 | 700 | 22831.2 |
| Himachal Pradesh | 1260200 | 1.70 | 731 | 21423.4 |
| Kerala | 5715800 | 12.80 | 794 | 731622.4 |
| Union territories | 226700 | 3.60 | 908 | 8161.2 |
| Jammu and Kashmir | 1017000 | 1.10 | 985 | 11187 |
| All India | 160868100 | 42.30 | 553 | 68047206.3 |

power. Solar power based products will allow villagers to use lighting and cook food without the use of kerosene. For villagers, solar provides a highly cost effective option and can provide power for a wider range of other uses like water heating water pumps for irrigation [16].

- **Environment Friendly**: Carbon mitigation—India faces enormous challenges in sustaining growth while addressing global warming. Country is the 5th largest emitter of greenhouse gases. India is already under pressure from developed economies to reduce emissions. Solar Energy can help make the power sector more efficient and help in reducing carbon gases [17].
- **Economic growth**: Lack of electricity infrastructure is one of the main hurdles in the development of rural India. There are no small scale industries in ***villages*** to provide ***employment*** to educated youth. Globalization has changed urban India but much of rural India, people still live in mud houses without any proper means of electricity. And development cannot happen without electricity. Many

young people move to urban areas and metros in search of jobs. No qualified youth wants to live in villages as there are no work opportunities. If solar industry picks up in villages, it will provide employment to local people in their hometown. This will stop migration to urban areas, which are already over-populating [18].

- **Grid based power generation not feasible**: Solar Power Plants are necessary for providing electricity in remote hilly areas of India where it is not possible to provide grid power. Also—problems of power theft are rampant in rural areas of India. Power distribution is now being privatized. Private companies cannot afford to lose money in power theft. Therefore, these companies are not willing to provide electricity to rural areas as the cost of power distribution to villages is high [15].
- **Off Grid power sources are recommended solutions for rural India**: Solar power has no connection to electrical grid. Since these solar PV modules will not be connected to the central grid, so there are no issues of safety issues, regulatory issues or liability insurance issues [19].
- **Productivity**: Shopkeepers can work later in the nights increasing their incomes [20]. The researchers also found that the solar lanterns particularly benefited schoolchildren and women. Although 70 % of the villages are connected to the power grid, they do not receive power early in the morning and in the evening because the state power company redirects electricity to major towns and cities [21, 22]. However, with 6 h of light supplied daily by the solar lanterns, study hours increase, giving a positive impact on the children's performance at school. Women are also able to perform their routine household work both indoors and outdoors during power outages.

## 6 Barriers to Adoption

The high initial cost of the solar lantern can be a great barrier for the implementation and distribution of the product. The cost benefit of acquisition of the solar lantern pays for itself after a period of time as showed in the economic analysis. Another barrier that can interfere in the adoption of the product is the that people who live in villages have no idea how the concept of credit works, for them it is not easy to understand that the monthly payments will go toward the acquisition of the product and there is no need to spend their incomes with kerosene for lighting any longer. It is necessary to have a person who can explain the process and guide the villagers to better understand the concept of credit and the importance it can be in their future with the Solar Lanterns [23].

The promotion channel in locals like the villages in India works as word of mouth, because the users are primary low educated farmers they might have problems understanding the convenience of the product as well the benefits that can be getting from it.

## 7 Model for Solving the Problem: Major Players

Adoption of Solar Lanterns in villages needs collaboration with many different players. These involve different govt. agencies, manufacturers, small scale banks and nonprofit organizations. The role of different stakeholders is described below.

1. ***Technology Manufacturers***: Solar energy based products needs to be customized for villages. Villages have a different requirement from cities and different environment. Products developed must satisfy basic needs instead of having lots of features and these products must be able to work in rugged conditions. Product costs must come down. Economies of scale in both production and logistics can effectively lower costs, but maximizing energy production and storage must be at the forefront in the minds of manufacturers.
2. ***NGOs and Village Leaders***: **International Development Agencies**: International Agencies like—World Bank, Asian Development Bank, United Nations Development Program, US Agency for International Development have a major role to promote adoption of solar technology based products in poor villages of developing countries. Villagers must be educated on the advantages of solar powered lighting and its benefits. Due to lower education levels, villages depend a lot on the village leaders and voluntary organizations to help them in understanding new products and technologies. All parties easily identify the initial benefits, but community development efforts should focus on the long term value. Many rural villagers, and by association, the NGO's that support them, do not have the long term vision to encourage investing in a product that will help to improve living conditions over its useful life.

"The World Bank" has sought to advance the diffusion of solar photovoltaic (PV) technology for **OFF Grid Applications** in the developing world. The World Bank recognized early on that investments in rural electrification through conventional grid extension would have to be selective. Thus, by implication, many rural households in the developing world would not receive a grid connection [3].

There are many nonprofit Organizations that are trying to sell solar lanterns in India. Beyond Solar is one of them. As per this company, while the long term economic benefit of the lanterns is apparent; the increased weekly installment requirements may prove too much for the average villager to commit [24].

"SELF (Solar Electric Light Fund, Inc.)" is another non-profit charitable organization in India to develop and facilitate solar rural electrification and energy self-sufficiency in developing countries. The web site gives information about the current events in the solar community, SELF's renewable energy projects, solar electricity, and photovoltaic technology [25].

- ***Lending Institutions***: As the upfront cost of a solar Lantern is extremely high and frequently do not have access to capital, financing is an extremely important component for success of solar energy for villages. Installment schemes need to be worked out by banks and financial institutions. Villagers need small amounts of capital via loans to buy items of basic necessities. Special micro-lenders will need to be established in villages as loans offered by regular retail banks do not fit the requirements of villagers. Micro-lenders can establish business units focused solely on deploying distributed renewable energy solutions on a large scale. Through further research and analysis, large scale implementation can become a realistic and profitable venture. Banks and financial institutions need an appreciation of renewable energy systems and an idea of the different benefits, risks and cash flows associated with renewable energy systems.

- ***Central and Local Governments***: Government needs to play a major role in the adoption of Solar Lanterns. Government's main role is to make the product affordable by providing subsidies—so that the product adoption can reach a critical mass. Once the product is used by 16 % of the consumer base, others will follow.

## 8 Development of the Model

As Rogers [26] pointed out, diffusion of innovations is impacted by the environment. So the following elements are required for the diffusion.

**Promotion and Awareness**

In villages, word of mouth publicity is the main method of promotion. Early adopters of a product are generally the village leaders. Villagers purchase products based on the experiences of the neighbors and village leaders.

Advertising through SMS messages—Although Indian villages have problems of electricity, but mobile phones are penetrating the rural population very fast. Some high earning villagers carry mobile phones. Therefore, one medium to reach them is through SMS Texting. High school kids need some light arrangement desperately for their board examinations. Government can help in promoting solar lanterns by giving incentives to students to use these for their higher studies.

**Sales and Distribution**

We are recommending that Post Offices can be used as channels of retail and distribution. Generally all villagers use post office services. Display and demo of lamps at post offices will create awareness. Also, villagers have a high trust in post offices as these are Government entity. They even maintain simple savings accounts at post offices. So buying their lamps from post offices and making a monthly payment at post office will be very convenient for the village people. There are less chances of fraud at post offices. All transactions will need to take place locally and post offices can be the conduit for that.

**Financing**

Villagers have unique financing requirements. As they are not well educated, credit concept is not very well understood. We are proposing that villagers own the lantern free and clear. We are proposing that Post Offices can provide financing for the lanterns. Also, villagers will need to make a monthly payment at the post office as they trust the post office system. Villagers will not be comfortable sending money to companies/banks located in other cities.

**Repair and Maintenance**

The post office will maintain a stock of some extra lanterns to replace the defective lanterns. However, the post office will not repair the lanterns. They are just a shipping center to send the defective lanterns back to manufacturer. Also, manufacturers can have a mobile technician, who travels to different post offices in the region and can repair the lanterns on the spot and take the defective lanterns back to the manufacturer. Moreover, since these lanterns have four major parts, there is no component level repair involved. If a module is defective, technician can just replace the defective module.

## 9 Conclusion and Recommendations

Many argue that renewable energy "costs more" than other energy sources, resulting in cost-driven decisions and policies that avoid renewable energy. In practice, a variety of factors can distort the comparison. For example, public subsidies may lower the costs of competing fuels. Although it is true that initial capital costs for renewable energy technologies are often higher on a cost-per-unit basis (i.e., $/kW), it is widely accepted that a true comparison must be made on the basis of total "lifecycle" costs. Lifecycle costs account for initial capital costs, future fuel costs, future operation and maintenance costs, decommissioning costs, and equipment lifetime. Here lies part of the problem in making comparisons.

Solar powered lighting has a tremendous impact on the lives of rural people without electricity. In both quantitative economic terms as well as qualitative lifestyle conditions, the benefit derived from such a simple device is irrefutable. Users of the lighting systems increase productivity and income, while safety, education, health, and general quality of life all benefit. Yet wide scale deployment of solar powered lighting has yet to take place. To facilitate the large scale deployment of solar powered lighting, private enterprise must be involved.

There is no doubt that solar lanterns can change the life of villagers in India. Energy is the main pillar of health and education improvement for life of people. Solar energy offers the most practical solution to overcome the energy demands of India's rural sector. By overcoming the challenges of finance, culture, and distribution, solar powered lighting systems can become a reality in much of the developing world. This will create a sustainable, environmentally friendly, and dignified way to improve the lives of millions of people and help in the efforts to alleviate poverty. Solar Lanterns can bring overall happiness in the life of villagers, as the improvements in productivity, education, health and income will ultimately lead to better quality of life.

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# Adoption of Energy Efficient Technologies from a Demand Side Management Perspective: Taxonomy of Adoption Drivers, Barriers and Policy Tools

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**Abstract** Energy efficiency is considered an alternative to building a power plant. However products and services enabling these efficiencies sometimes hit bottlenecks in adoption. This chapter reviews this important issue.

## 1 Barriers Research Approaches

An extensive research effort has been put towards identifying the barriers and drivers associated with adoption of energy efficient technologies. Studies have been conducted with respect to various different contexts such as; are country, technology, industry, energy intensity and many others. In this study, a special effort is going to be focused on understanding body of barrier studies in these contexts. It has been observed that barrier studies show contextual difference in terms of variables such as; case technology, country, industry and organization related characteristics, methodology employed etc. This section is going to review and analyze energy efficiency barrier literature as well as touch on criticisms attracted by other approaches.

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### 1.1 Effect of Barriers to and Drivers for Energy Efficiency Investments

One of the most comprehensive and recent barrier models has been developed by Sorrell et al. [62]. Proposed model has been applied in organizations serving under higher education, brewery and mechanical sectors in each of the countries Ireland, Germany and UK. Accordingly, suggestions for improving existing policies have been stated for organizational, sector and national levels. It has been observed that adoption barriers are ranked differently depending on the contexts; country and sector. Thus, it has been stated that one type fits all kind energy efficiency programs are not suitable for large scale energy efficient technology adoption. As a result, requirement for more comprehensive analysis of market segmentation and alignment of related policies have been stated [62]. A recent study has been conducted by Thollander and Ottosson [67] to explore and rank barriers and drivers to implementation of cost effective energy efficiency measures in Swedish pulp industry. Results imply that there is an energy efficiency gap in the Swedish pulp industry and majority of the barriers are related to market related failures whereas some of the most important barriers are related to inexistence of organizational capabilities to absorb energy efficiency technologies within the firms. Thus, market interventions cannot be effective in influencing adoption decisions. Biggest barriers to cost effective energy efficiency investments were found to be risk of production disruptions, cost of production disruption/hassle/inconvenience, inappropriate technology, lack of time and capital, existence of other priorities and slim organizational structure. Surprisingly, the most significant driving forces for energy efficiency investments were found to be efforts put by employees with environmental awareness and existence of long term energy strategies within the firms where as efficiency gains is ranked relatively low. Additionally, potential increases in cost of energy, electricity certification system and long term agreements have been observed to be significant drivers as well. Based on the different regions and industries barriers and drivers to energy efficiency measures are stated to differ. Thus, one size fits all type energy policies have been stated as not being effective and as a result energy policies are suggested being more diversified depending on significant factors [62]. An improvement area derived from this study emerges from the fact that some of the most significant energy efficiency barriers such as; lack of time, existence of more important duties, slim organizations, lack of staff awareness, long decision chains are organization related barriers, but not market failure; thus, traditional market based interventions cannot be helpful. Further studies are advised to look into reducing organizational and behavioral barriers within the firms [67]. Another study conducted by Rohdin and Thollander [52] has focused on non-energy intensive industrial organizations. Accordingly, aim of the study has been stated to investigate barriers to implementation of energy efficiency measures in the Swedish non-energy intensive manufacturing industry. Major barriers are found to be cost/risk of production disruption/hassle/inconvenience, lack of time and sub metering about energy efficiency conservation, existence of other prior tasks or capital investments, cost of gathering information about an energy efficiency measure and split incentives with energy service providers. Also, an example for market imperfection that inhibits energy efficiency adoption has been observed through a market oligopoly forced by a few manufacturers who can dictate the market. Important drivers for energy efficiency measures are found to be long term strategic energy policies, increasing energy prices, people with environmental awareness within the company where as environmental management systems were not found to promote adoption although it has been shown to be a contributor in a prior study [62]. Barriers and drivers to adoption of energy technologies and management practices are advised to be researched for the case of non-energy intensive industries [52]. Differences between energy and non-energy intensive industries in terms of adoption of more efficient technologies have also attracted attention. Accordingly, Hasanbeigi et al. [23] has attempted to explore drivers and barriers associated with energy efficiency investments in textile and cement industries which are representative of non-energy intensive and energy intensive industries. Case study has been conducted among 16 SMEs in Thailand. Based on the results, authors have proposed improvements on existing energy efficiency policy frameworks, which consist of raising awareness and information and support of implementation action steps [48, 54, 78]. Proposed additional step has been stated to be motivation campaigns that promote raised awareness towards actions by use of policies which are setting accurate standards and regulations in place, providing demonstration projects and pursuing voluntary agreement campaigns. In textile industry it has been observed that existence of more important production related priorities, uncertainties about cost and performance about the newer technologies are the biggest barriers where as potential production disruptions caused by new technologies, investment cost and required implementation time are the biggest barriers for cement industry. Lack of internal coordination has been stated to be another barrier by textile industry as cement industry perceives lack of coordination among external entities. It has further been indicated that due to higher priority put over manufacturing, production managers have more power than energy or maintenance managers where energy efficiency related project proposals actually come from. As a result, power differences among organizational units have been stated to be a barrier to energy efficiency investments. Experts' judgments on barriers mainly emphasize lack of knowledge and uncertainties associated with new technologies at both operational and engineering levels. Top drivers for investing energy efficient technologies have been potential improvements on product quality, working conditions and reduction in energy costs. Interestingly, improving reputation and increasing recognition has been important for textile industry where as compliance with regulations has been rated as an important driver by cement industry which is perceived as environmentally harmful industry from public view. Findings also indicate another significant finding that might favor carbon tax debate that proposes incur more costs on carbon dioxide intensive businesses. Both textile and cement industries have ranked introducing more energy efficient solutions as an alternative strategy in case of increased energy prices while increasing prices of final products were ranked lower [23]. A barrier study in a small and medium enterprises context has been conducted by Thollander et al. [68] in Sweden in order to give insights about an energy efficiency program that has been undertaken in a Swedish region for promoting energy efficiency in manufacturing SMEs. Largest barriers identified in this study are related to existence of other prior tasks or investments, lack of access to capital which are non informational barriers although previous studies have shown that informational barriers about existing or upcoming technologies is a big inhibitor for adoption in case of SMEs [59]. This situation has been stated to be an indicator of auditing activities' success for this specific case. Additionally, employees with environmental awareness and existence of long term energy strategy are found to be highly ranked drivers. Although improvements in reducing informational barriers have been observed it has been stated that there are still open spaces for improvements in auditing procedures [68].

Apart from industrial context, adoption behavior of commercial and services sector has also been researched. For instance, Schleich and Gruber [56] have attempted to determine the relationship between a limited sample of energy efficiency barriers identified in the literature and energy efficiency investments in German commercial and services sector. It has been observed that statistical significance of explanatory variables is more heterogeneous in sub-sector level than sector level. This situation has been stated to be an indicator for supporting the inhibiting role of adopter heterogeneity. For instance, split incentives have been identified as an important inhibitor to energy efficiency among commercial and service sub-sectors as it was also proven to be so for private housing sector by a study conducted by Scott [57]. Moreover, lack of information about the energy consumption profiles of individual firms has been found to be playing an inhibitor role. Finally, low prioritization of energy efficiency related projects has been observed as a common behavior in sector level analysis. As a further research initiative, it has been stated that grounded research has been a main focus point in energy efficiency research, however empirical studies in energy efficiency has not been fully explored. Thus, more empirical research studies are required to reveal existence of market barriers and market failures for specific contexts [56].

## *1.2 Effects of Organizational Characteristics on Energy Efficiency Investments*

As observed from the research studies mentioned above organizational characteristics have been observed to have significant effects on energy efficient technology adoption. For instance, a study conducted by DeCanio [12] has attempted to observe organizational and economical factors on energy efficiency investments' payback periods. In the case study, it has also been observed that economical factors are not the only set of variables that can fully explain variations in energy efficiency investments, but also that organizational factors are significant in explaining firms' investment behaviors and decisions. As a result, it is concluded that even though economical benefits gained from energy efficiency investments might be the same given an action taken, organizations' level of interest differ depending on their characteristics [12]. This aspect has been studied by various researchers in different contexts. For instance, DeCanio [11] combined data acquired by questionnaires and interviews conducted on firms participating in Green Lights Program which was started in 1991 by Environmental Protection Agency. Purpose of the study has been stated to explore barriers to economically profitable energy efficiency investments. Findings show that; long payback periods, hurdle rates, dependence on overall managerial performance, existence of strategic priorities, control and monitoring problems due to decentralization, inappropriate incentives-tenant/owner problem, capital availability and bad experiences in the past can play inhibiting role against energy efficiency investments. Implications for corporate policies have been stated as creation of internal department that is dedicated to energy management for supporting internal incentives, monitoring and analysis of energy use, building awareness around energy conservation and environment [11]. A more recent and comprehensive study has been conducted by De Groot et al. [10] who have aimed to explore effects of market barriers, motives and organizational characteristics on energy efficiency related investment behaviors of various industries in Netherlands. Changes in firms' energy efficiency related investments and strategic decisions have been observed by using cases that incur different energy and environmental policies. It has been observed that potential cost savings is the most important driver for energy efficiency related investments where as existence of prior projects that may provide more return on investment and available lifetime for existing equipment are the most important inhibitors. Provided that profitability and international competitiveness will not be affected, firms are stated to be willing to adopt new environmental policies. Moreover, this attitude has been observed to be driven by firm size, energy intensity of the processes and competitive position of the firms. Future studies are advised to look into developing policies for promoting energy efficient technologies for energy intensive SMEs [10]. Significance of organizational factors have also been observed by Kounetas and Tsekouras [31] Accordingly, corresponding study has attempted to explain energy efficiency paradox by incorporating two different approaches which are profitability and adoption factors. Results indicate that firm specific characteristics have significant effects on decisions towards adoption of energy efficient technologies. It has been confirmed that firms with energy intensive processes, subsidies and regulations towards reducing environmental damage have positive effect on energy efficient technology adoption decisions. Moreover, available age of the existing equipment subject to replacement and uncertainty in the economic environment have been found to be negatively correlated to adoption decisions due to sink costs and organizations' tendency towards reducing input costs in an uncertain environment. On the other hand, barriers associated with energy efficiency technologies have been confirmed to affect adoption decisions negatively. What's more existence of research activities within a firm and profit margin has been found to be affecting adoption decisions negatively. This implies that energy efficiency related investments are perceived to have lower priorities in research intensive firms or firms with more payback expectations [31]. Kounetas and Tsekouras [32] have also analyzed energy efficient technologies' impact on Greek manufacturing firms' productive performance by utilizing trans logarithmic cost functions. Country and time specific variations in mind, it has been observed that adoption of energy efficient technologies have positive impact on technical efficiency where as its impact on productive performance. Moreover, energy efficient technologies have positive effect on the firms characterized as high energy intensive where as the opposite applies to low energy intensive firms [32]. Organizational characteristics have also been analyzed to understand their effects on information absorption [33]. For instance, objective of the study has been stated to determine the factors affecting the degree of energy efficient technology related information absorbed by energy efficient technology adopters. It has been observed that different forms of resource constraints are the major obstacles causing information barriers. For instance larger companies have been found to be reaching epidemic type technology information easier than smaller firms due to their advantages in information gathering and processing. However, the same relationship between amount of R&D activities and information acquisition has not been proven to be positive as innovation efforts, which are perceived as more vital, and energy efficiency related tasks are competing for the same resources. Thus, free technical support regarding technological information is proposed to be an appropriate mediator for information barriers. It has further been emphasized that firms' interest on different technologies is the main cause of heterogeneity in level of information acquisition [33]. Please see Table 1 for list of organizational variables studied in the literature.

### *1.3 Effects of Information and Decision Making Practices on Energy Efficiency Investments*

Use of different decision making practices in the organizations and its implications on adoption of energy efficient technologies has been another area of research. Harris et al. [22] has attempted to analyze the factors affecting firms' decisions on energy efficiency investments. Data has been acquired from an energy audit program called Commonwealth Government's Enterprise Energy Audit Program (EEAP) undertaken in Australia around 6 years until 1997. 100 firms have been surveyed and descriptive statistics have been presented. According to the findings, it has been observed that more than 74 % of the firms have indicated that they pay attention to environmental issues in their investment decisions processes, however methods used for evaluating investment alternatives have been observed to be solely financial methods such as; NPV, ROI, payback period and upper limit on debt/equity ratio. It has also been observed that main reasons for not adopting

**Table 1** Organizational variables studied in the energy efficient technology adoption literature

| Organizational variables | References |
|---|---|
| R&D and innovation activities | [31, 33] |
| Number of R&D employee | [33] |
| Cooperating with an external energy efficiency expert | [33] |
| Employing an internal energy efficiency expert | [33] |
| Information acquisition channels | [33] |
| Geographical location of the organization | [33] |
| Decision making practices in the organization | [33] |
| Firm size | [5, 31, 33] |
| Market concentration | [31] |
| Ownership structure | [31] |
| Financial structure of the firm | [31] |
| Scarcity of managerial time | [31] |
| Scarcity of skilled personal | [31] |
| Firm's age—learning by doing effect | [31] |
| Firm specific capital vintage | [31] |
| Decentralization | [5] |
| Delegation | [5] |
| Contract maintenance and priority | [5] |
| Managers' ability to pursue energy efficiency investments | [5] |
| Managers' ability to process different information types | [5] |

energy efficient solutions are stated as risks involved in the projects, belief that audit results are inaccurate, low rate of return, too long payback period, and lack of access to capital. That the most important drivers are economic variables is stated to indicate that firms go after the investments that have the highest benefit/cost ratios. This situation is also stated to be supported by claiming that organizations do not have the techniques that can incorporate other factors related to business practices such as quality, scheduling, cycle times and so on. Another interesting finding is that average of $88000 has been invested by all firms where as average cost of all audit investment recommendations were $121000. This result is stated to support findings of another study conducted by Thollander et al. [69] which states that firms tend to invest more on smaller investments rather than costly ones. Moreover, effects of risk on investment decisions have also been observed to prevent energy efficiency investments and majority of the firms have been stated to agree that constant changes on information, adjustment costs during and after the installations and potential costs associated with breakdown of the new systems are the main risks. Existence of risks is observed to increase expected rate of return from investment projects which is named as "hurdle rate" barrier in the literature [22]. A study conducted by Harris et al. [22] has revealed that 80, 53, 30 % of the companies have been using payback period, IRR and NPV respectively whilst dealing with making investment decisions. Moreover, Pye and McKane [49] and Ramesohl et al. [50] have stated that non financial criteria are also used in assessment models as well where as Harris et al. [22] have claimed the opposite.

Combined with uncertainties and risks associated with future, decision-making becomes a very complex system. Simon [60] claimed that maximizing multiple objectives is impossible due to complexity of decision-making, so purpose of companies is stated to reach satisfying results rather than optimized solutions. This phenomenon is called bounded rationality and has been widely studied in barriers to energy efficiency literature.

Sandberg and Soderstrom [54] have attempted to understand decision-making processes and variables used in large organizations from a managerial perspective with an emphasis on energy efficiency technologies. Decision processes have been analyzed with respect to four interrelated subjects which are energy auditing, monitoring and benchmarking practices, investment routines of the organizations, follow up and knowledge transfer, and risk management and uncertainty. Responses from the interviews have been observed to often emphasize the necessity of having a wide spectrum of assessment criteria that deal with potential consequences of energy efficiency investments on non-financial parameters such as; environmental improvements, increased production efficiency etc. Another study conducted by Thollander et al. [69] have addressed some of this issue and proved that information regarding manufacturing related consequences of an energy efficiency investment may help adoption decisions positively. Sandberg and Soderstrom [54] have stated the necessity of accessing clear and accurate information by giving a practical example, which refers to difficulty of obtaining energy consumption data due to high temperatures or type of energy used in the process. This situation is stated to limit the ability to realize potential savings that can be derived from energy efficiency investments. It has also been realized that firms often tend to delay their replacement investments as long as possible as it is perceived as the cheapest alternative of all and this situation is stated to emerge as a barrier to energy efficiency investments. Risk management practices have been observed to be widely used by both of the industries and it has also been observed that their investment decisions are highly risk averse.

Decentralized organizational structures have also been observed to be having difficulties in following consequences of investment decisions due to difficulties in knowledge transfer from one facility to another. One significant finding is stated to refer to the fact that large organizations tend to outsource energy efficiency related projects, as they are perceived as non-core business activities. Future research initiatives have been suggested looking into potential effects of outsourcing energy efficiency related projects on diffusion of energy efficiency technologies. Dynamics between internal and external actors is stated to bring up new problems as well as opportunities [54]. An interesting study has been conducted by de Almeida [9] in order to explain the relationship between energy efficiency gap and market forces. Study has analyzed limitation of market forces with respect to variables such as; market agents' characteristics and their decision-making processes and transaction types. It has been observed that split incentives is an inhibiting factor for diffusion of high efficiency motors (HEMs) in French motor industry. Motor manufacturers in France are stated to align their manufacturing and marketing practices based on the market, which is stated to be not aware of the opportunities of high efficiency motors over existing models. Due to existence of a market associated with information asymmetry manufacturers are stated not to intend to promote HEMs claiming that there is no interest in the market. Furthermore, market agents' decision practices have also been found significant on market forces. Based on the agent characteristics, agents' perceived value from energy efficiency feature has been found to be relatively low compared to set of other product features that are taken into consideration in decision making process. Due to constraints involved in agents' decision making processes adoption of HEMs has been found to be low. Suggestions for removing imperfect information in the market have been stated to be establishing standards and labeling programs along with a more comprehensive DSM programs [9].

Dieperink et al. [15] has attempted to combine different perspectives employed in Dutch diffusion literature in one framework in order to provide a more holistic approach for policy makers and diffusion scholars. Diffusion literature explaining the slow diffusion rate of energy efficiency technologies has been stated to focus on different pieces of a sophisticated problem. Both economical and behavioral models individually have been claimed to be lacking explaining the energy efficiency gap. Difference between widely accepted studies conducted by Rogers [51], Kemp et al. [26] and Daft [7] have been stated to be that corresponding framework is centered on decision making process and assessment rather than considering it as a small part of a bigger adoption process. As stated, focus point of the proposed framework is decision making process and assessment combined with company characteristics. This built is stated to enable understand the mechanism of other influences which are economic and technical aspects of the technology, macro developments in the business environments and company context which refers to government, market and societal variables. Based on the framework, given more complex and detailed decision models can be drawn and validity of them can be tested by employing questionnaires asking different actors' judgments about relative importance of explanatory decision variables. Results can provide valuable information regarding the direct and indirect effects of decision variables on potential adopters' priorities. Implications from the results are stated to be a strategic tool to develop more accurate policy tools [15]. Along with Dieperink et al.'s [15] work, Vermeulen and Hovens [72] have applied integrative framework [15] for explaining diffusion of energy innovations adoption for the case of new office buildings. Two levels of analysis have been employed to determine relative representativeness of variables which are nature of decision making, economic, technology and company characteristics, government policy and influences from market and society. First level analysis attempts to find out relative importance of assessment variables and nature of decision making process over energy innovation adoption decisions. Second level attempts to further explain the effects of variables over assessment and process variables. Findings are stated to show that for the case of newly diffusing technologies economic assessment criterion along with non-financial criteria and process aspects have been significant in explaining adoption decisions where as mature technologies' adoption is explained by routine applications given that the innovation is favorably rated with certain assessment variables which are economic performance, functionality and technical fit. Moreover no statistical significance has been found for supporting government supported information campaigns' on promoting adoption decisions where as suppliers' promotions have been proven to be effective. Lastly, energy performance standards and subsidies have been found to be effective for promoting adoption of both diffused and newly diffusing technologies with a slightly more effect on newly diffusing technologies [72].

## *1.4 Criticisms on Barriers Research Approaches*

Koomey [29] has identified four causes that might result in low adoption of energy efficient technologies. These causes are stated as hidden costs, wrong parameter specifications, marketing acceptance time lag and market failures. Koomey's [29] research methodology has employed two measures one of which is more energy efficient and compared them against each other. Results of the study has shown that although there was no significant difference between the energy efficient technology and the baseline technology in terms of hidden costs, parameter specifications, marketing acceptance time lag and market failures, adoption of energy efficient alternative was still slow. Based on this, it has been claimed that economic models are not fully capable of explaining energy efficiency gap. Accordingly, it has been suggested that more emphasis on behavioral research should be put in order to address economic models' weaknesses. Particularly, it has also been suggested that further studies should be specifically focused on very small niches by defining market segments, end use, technology and type of operation [29]. The claim that adoption decisions may not always be explained by economic principles has also been supported by Weber [74] who has suggested combining behavioral approaches with traditional barrier studies by reviewing barrier models and give insights about their weaknesses. One of these weaknesses is stated to be barrier models' energy efficiency potential which is achieved by favoring only technical solutions and positive actions. Barrier models are stated to make wrong assumptions by defining improved energy efficiency as a result of positive actions, which may refer to purchase of more energy efficient products, but omission of actions that inhibit excess energy use is not considered so. This assumption is claimed to block all potential energy conserving options that is based on negative actions. Barrier models are also stated to focus on minimizing energy consumption without justifying the potential implications of the action taken. This situation is stated to prevent barriers from going further than technical solutions by neglecting social aspect of the issue. Another assumption associated with barrier models is stated that potential energy efficiency is the energy consumption derivation between existing and state of the art technologies without considering behavioral methods that can help utilize energy use and increase energy efficiency through changing users' energy behavior. However, regarding definition of energy efficiency a previous study, which is a widely cited by many energy researchers, conducted by Jaffe and Stavins [25] seems to have been neglected.

## 2 Psychological Research Approaches

There is a considerable amount of behavioral research studies attempting to explain energy conserving behavior as well as acceptance of energy efficient, in some cases referred as clear production, technologies in the psychology literature. Psychological research studies contributing to energy efficiency studies have been gathered together by Stern [64]. For instance, particular study has been covering the years from 1970s to 1980s. Accordingly, traditional policy analysis approaches have been stated to focus on two aspects of diffusion which are namely finance and information. What psychology based research studies have criticized most about traditional approaches is that policy analysis underestimates significance of different levels of money or information wise interventions by mostly focusing on amount of resource invested rather than their implications on user decisions. Information programs have been stated to fail due to less attention given to importance of information delivery [13, 17]. This is also supported by several researchers acclaiming that information is more effective when it is specific, vivid and personalized [4, 65, 66]. For instance, case studies have been mentioned to support different aspects of information delivery such as observation that closed-circuit video programs change user behaviors and provide more energy savings than paper based energy consumption reports [76] and constant reporting of the energy consumption support energy saving behavior [58]. Morgenstern and Al-Jurf [39] have analyzed effect of free information on commercial buildings' energy efficient technology adoption decisions. Case study has focused on lighting technologies, which are namely compact fluorescent, occupancy censors, and specular reflectors. A dataset acquired through a survey conducted by United States Department of Energy on commercial buildings energy consumption and expenditures has been analyzed. It has been concluded that free information has positive effect on commercial buildings' adoption decisions on energy efficient lighting technologies. For instance, it has further been realized that free information has more positive impact on adoption decision of those organizations that have already invested in advanced lighting systems than first time investors. This situation is stated to imply that user heterogeneity affects impact of free information [39].

## 2.1 Effects of Peer Evaluation on Technology Adoption

In the literature it has also been observed that some non-expert suggestions have had significant influence on consumer decisions [8, 35]. Existence of this situation is stated to support importance of information source on energy saving behavior. Moreover, credibility has been determined as one of the significant variables associated with information source as it has been observed by local energy programs' efficiency and success due to existence of established trust in local environment [19, 45]. Another branch of research studies have been focusing on consumers' perception about the costs associated or incentives provided [63]. Existence of householders that value dollar savings more than electricity savings is an example that has been provided to justify the point [27]. Future energy research studies such as; forecasting, evaluation, implementation techniques for energy efficiency programs are suggested being enriched with psychological variables rather than just technical and economical [64].

## 2.2 Effects of Technological Characteristics on Information Processing and Decision Making

Evaluation of energy audits conducted in Swedish industry implies that firms focus investing in low-cost measures such as; ventilation, lighting and compressors rather than more strategic measures such as manufacturing systems [68]. Reasons for such investment behavior has been found out to be risks involved in manufacturing disturbances, lack of access to capital and budget funding [52]. Depending on the project size, existence of different organizational behaviors towards investments has also been supported by Björkegren [3]. Basically, corresponding study states that organizations tend to approach big projects as an organizational learning process rather than a traditional project management approach [3]. Based on this, Thollander et al. [69] has attempted to explore use of optimization tools in order to provide additional information about potential implications of strategic energy efficiency investments on manufacturing related variables. Potential energy savings information provided by traditional auditing systems has been observed to be lagging in promoting costly investments. Findings suggest that in order to promote adoption of high cost energy efficiency investments it is important to inform decision makers about investments' potential effects on core business. Thus, energy audits may need to provide firms' with strategic information such as potential competitive advantages and higher productivity that can be gained aside from reduced energy costs only. Further studies can incorporate results of this study into manufacturing simulation models to observe the potential strategic energy efficiency investments' effects on production related variables such as scheduling, bottlenecks, quality and so on [69].

## 2.3 Effects of Organizational Human Factors on Energy Efficient Technology Adoption

Sola and Xavier attempted to find out the relationship between organizational human factors and levels of energy loss by surveying 40 Brazilian firms, which consist of pulp and paper, food, wood, and chemical industries. Research framework for determining factors affecting energy efficiency has been based on a study conducted by Meier et al. [38]. Framework approaches evaluation of energy efficiency from three factors; which are construction factor, which refers to level of technology embedded in a product or a service; operational factor, which refers to optimum operation level of a product or a service with respect to energy consumption; and maintenance factor, which refers to lost energy due to equipment wearing out. One of the most interesting findings of this study is that the majority of energy loss occurs because of operation and maintenance related issues rather than construction. This indicates the importance of energy consumption related behavioral issues in the organizations. Regression between organizational human factors and energy loss data obtained from sample electrical motors has revealed that level of cooperation between employees, incentives for collaboration between companies and universities, employee education, existence of future vision on energy technologies and policy for long term energy efficient technologies, firm receptivity of new ideas, use of energy consumption data in production management, and monitoring energy quality have been found to have negative correlation with energy loss. This is stated to indicate that firms with characteristics mentioned above are more likely to conserve energy. Based on the findings authors suggest policies on promoting use of energy management procedures, establishing collaborations between universities and organizations as well as long term energy efficiency policies, incentives for employee education, and more receptive culture towards energy related ideas. Further research initiatives have been suggested to focus on developing mechanisms to promote collaborations between universities and companies as well as studying more comprehensive set of factors that impact conservation behaviors in organizations [61]. Please see Table 2 for list of human factors studied by Sola and Xavier [61].

Due to difficulties in explaining energy efficiency gap with engineering and economics based barrier models Cebon [5] has analyzed energy efficiency gap with organizational theory perspective by observing the interaction between technology and organization specific variables. Study has found out that energy efficient technology adoption decisions can be explained by two different levels. First level explains adoption decisions by analyzing managers' ability to process different information types, which are named as technical, contextual and connected information as well as decision makers' influence to drive the actors towards a defined goal. Second level refers to adoption decisions by analyzing effects of organizational structures, whose explanatory variables are named as decentralization, size, delegation, contract maintenance and priority, on managers' ability to pursue energy efficiency investments. Findings suggest four strategies

**Table 2** Human factors related to energy efficient technology adoption [61]

| Areas | Human factors |
|---|---|
| Management system | Adequacy of work place |
| | Adequacy of work-load to the people |
| | Adequacy of tasks complexity to the individual potential |
| | Internal cooperation between managers of departments |
| | Action of the company to motivate the staff to the work |
| | Integrated management: energy, environment and technology |
| | Quality management procedures |
| | Energy management procedures |
| Employees | People motivation to work |
| | Initiative to learn and to present projects in the company |
| | Level of professional cooperation between employees |
| | Level of personal cooperation between employees |
| Education | Incentive and support of the company for employee's education |
| | Initiative of the company to search partnership with university |
| | Initiative of the universities to search partnerships with the companies |
| | Initiative of the company for qualification in training institutions |
| Strategic vision | Future vision on energy and technology |
| | Policy of long-term for energy-efficient technologies |
| | Policy for energy and energy efficiency in the company |
| | Receptivity on the part of company for ideas and projects of employees |
| Energy management | Use of energy indicators in the production |
| | Reduction of electricity energy cost for adequacy of the tariff system |
| | Initiative of the company to efficiency projects with energy concessionaire |
| | Using of software for diagnostics and projects on energy efficiency |
| | Study and monitoring of electric energy quality |
| | Use of industrial nets by company for monitoring of energy losses |
| | Implemented procedure of periodic energy auditor ship in the company |

that can be utilized for improving energy efficiency policies. First strategy (select technologies which fit existing organizations) suggests that energy efficiency policies should promote those technologies which are likely to be adopted by existing organizations due to compatible characteristics. Second strategy (reconfigure technologies to fit existing organizations) suggests utilizing information campaigns that can help organizations understand the technology better. Depending on the feedback coming from the adopters technologies can be modified in the long term. Third strategy (select organizations likely to be receptive to target technologies) suggests analyzing absorption capacity of the organizations with respect to different technologies and providing incentives to those which are more likely to be adopted easier. Last strategy (modify organizations so they can select the technology) suggests providing interventions that can eliminate power problems within the organizations such as providing credits, funds for energy efficiency specific projects in organizations [5].

## 2.4 Relationship Between Economics and Energy Use Behavior

Nassen et al. [43] has analyzed short and long term price elasticity of Swedish residential buildings' space and heating energy consumption by using the data gathered for the years between 1970 and 2002. Analysis employs income levels, time and energy prices as independent and energy consumption as dependent variables and attempts to determine the consumers' reactions towards energy price changes. Price elasticity have been divided as short and long term in order to observe effects of price fluctuations on direct impacts and large energy efficiency investments respectively. Findings claim that there is significant but a very low correlation between energy consumption and energy prices in the case of existing buildings however the same relation does not exist for the new buildings. Payoff between comfort and energy savings has been shown as one of the reasons behind low price elasticity since energy consumption is just 3–4 % of the total expenditures in Swedish residential buildings. This point has also been stated to be studied by a prior behavioral study [16]. In order to get insight to what other factors might have been influential, authors have interviewed with experts working in government and commercial organizations. Accordingly, it has been acclaimed that split incentives and transaction costs associated with information gathering on energy efficient technologies have been a major barrier. Interestingly, for the case of new buildings existing; national building energy standards have been stated to be a significant barrier due to its norm based nature rather than providing a minimum standard for energy efficiency [43].

## 2.5 Educational Programs as Policy Tools

As mentioned by Weber [74] technical or engineering based energy model approaches promote replacement of existing technologies with more efficient alternatives and lack focusing on changing human behavior and promote conserving energy. As also can be realized from the sample of studies mentioned above behavioral research approaches promote educational policy tools as a solution. For instance, it would be beneficial to focus on a study conducted by Dias et al. [14] who has attempted to address energy efficiency barriers from a pure behavioral perspective. Study has aimed to resolve short and medium term energy efficiency barriers by adding an educational system perspective on Haas' [21] basic schema of interactions between individual behavior and external factors in energy context. Proposed framework is anticipated to address energy efficiency related barriers associated with lack of awareness and human behavior. Case study has shown that typical Brazilian consumer is not aware of rational use of energy due to the fact that awareness programs are already in position. Inclusion of energy related education in schools is proposed to play an important role in utilizing students as educational agents in their families and in the medium run steer society towards being more responsible in smart use of energy [14].

## 3 Socio-Technical Research Approaches

In his article, Lutzenhiser [36] has discussed some of the weaknesses of energy efficiency research studies that are associated with economical, engineering and psychological research perspectives; and proposed an approach aiming to address social context of the energy efficient technology adoption. For instance, these weaknesses are stated as; engineering based systems approach energy consumption by focusing on the technological aspects and underestimate human factors that cause different energy use profiles. This point has been supported by the example of users' tendency to change factory settings or even use things different than they were actually intended in case of air conditioning or heating systems. Reason for this situation is stated to be the fact that products or systems are designed for average customer needs rather than whole range of customers with different requirements. Thus, consumers whose needs are outside the level of what product can offer are not satisfied by the average conditioning levels. On the other hand, economical energy use models have been stated to have two weaknesses one of which refers to existence of two conflicting forces, which are various decision variables and users' bounded rationality; and lack of ability to explain the dynamics behind the causal relationship between price and demand changes, staying at a level that helps experts verify whether the relationship exist or not. Achieving level of detail that can give insights to the dynamics behind the causal relationships has been stated to be a key for designing better energy policies. Apart from technical and economical energy use models, psychological attitude models used in energy use models have also been stated to fail due to misconception. Accordingly in order to address some of the gaps existing in traditional energy use research approaches, Lutzenhiser [36] proposes a social energy use model that attempts to address impacts of social norms, culture, social network on energy use based on previous studies stating that energy is a center piece of socio-cultural change as also emphasized by many other researchers [1, 6, 53, 75]. Cultural model is proposed to have three levels of applications which are descriptive, explanatory and predictive analysis of energy consumption. Descriptive level involves explanatory research that maps existing cultures and lifestyles in a given area where as explanatory level deals with rationalization of the reasons why different life styles have different energy use behavior. This level is stated to help identification of the relationships between variables and provide a basis for smarter policy intervention. Third level which is predictive stage is stated to use the data provided by empirical research studies that have been conducted in the first two stages and help design better forecast models for future energy consumption as well as provide data for adoption decision models with respect to different consumer groups [36]. Parallel to afore mentioned study Lutzenhiser [37] has looked into understanding barriers to energy efficiency technologies by observing organizational networks' effects on technology diffusion. Results of the study provide wide range of barriers to energy efficiency investments. For instance, it has been stated that small changes in interest rates are rapidly impacting construction companies as well as the whole supply chain including material suppliers, land and labor market. Resulting from a highly uncertain market structure, actors are stated to have tendency to be risk averse. Moreover, existing business practices driven by consumer desires and demands in the construction industry have also been found to create barriers to diffusion of more energy efficient technologies. One of business practices have been acclaimed to be standardized building designs which are more energy efficient but less consumer-favored, and customized building designs which are more consumer-favored but less energy efficient. As also supported by de Almeida [9] organizations react to market needs and as a result market is not aware of new energy efficient technologies, on the other hand as market is not aware of energy efficient technologies there is no demand for new technologies and as a result organizations do not tend to make use of new technologies. As a result, diffusion of energy technologies tends to be slow due to negative feedback loops between market actors' actions. Existence of such contradictive forces with organizations' main objective has been found to be inhibiting positive actions towards energy efficiency investments. Another important business practice causing construction organizations to disfavor adoption of more energy efficient technologies is firm size. Due to operating in different regions or countries, construction companies tend to promote standard designs that enable mass production which decrease costs and increase quality. As a result, standard designs in climate zones, where standard designs are not intended to be built for, consume more energy than region-customized alternatives. Competition and its implications on energy efficiency investment decisions have also been analyzed. Interestingly, existence of either too strong or weak competition among construction companies has been found to cause barriers which are namely risk aversion and complacency consecutively. Moreover, long term stability requirement let by large scale manufacturing and distribution systems as well as hidden costs associated with construction industry, industrial and organizational level inertia have also been identified as barriers to energy efficient investments. Significance of information related factors over energy efficiency investments has also been mentioned in the study. With respect to information channels, receivers and environment other external variables; perceived trust and validity of the information have been found to may or may not inhibit actions towards energy efficiency investments. Additionally, different user cultures, organizational power conflicts, adopters' difficulty in accessing capital, codes, standards, utility practices and counter acting trends have been found to be important factors in energy efficiency adoption decisions. Further research initiatives have been suggested to focus on exploring the effect of design on users' decisions on energy efficient investments. Role of decision makers along the supply chain is advised to be analyzed with respect to socio technical approaches [37].

## 4 Life Style Analysis Research Approaches

It has been observed that residential energy efficiency studies are making use of life style analysis approaches more than industrial and commercial studies in attempting to explain adoption of energy efficient technologies. Although there is considerable amount of life style analysis regarding the residential energy efficiency context we will present some of the recent works as a representative sample. Andrews and Kroggman [2] have focused on explaining the relationship between US commercial buildings' adoption of energy efficient heating, cooling, windows and lighting technologies and explanatory variables that are specific to building characteristics, occupant activities and region. It has been observed that energy efficient technologies are mostly being adopted by new buildings due to feasibility of initial costs and design efforts. For instance, split incentive barrier has been proven to be significant in adoption decisions. Owner occupied buildings have been found to be adapting energy efficient technologies more than rental buildings. Implications from the study suggest that existing buildings offer a huge energy efficiency potential, but adoption rates in these buildings are slow. Thus, market barriers associated with existing buildings can be addressed with new policies. Relationship between adoption of individual innovative technologies and new high performance buildings should be explored. How energy intensity and efficiency relates to each other has been stated to be another area of research [2]. A similar study has been conducted by Nair et al. [41] has surveyed the factors that are proposed to affect Swedish residential house owners' energy efficiency investments. Factors are divided into two clusters which are namely personal and contextual factors. Descriptive statistics show that perceived annual energy cost has a positive correlation with energy efficiency investments where as annual income does not have the same pattern. In particular, middle income groups show higher investment initiatives than high income groups. Younger population groups have been identified as having tendency to invest in energy efficiency more than older age groups. It has also been found out that higher education levels lead more energy efficiency investments than lower levels. Furthermore, it has been observed that some geographic locations show tendency to invest in energy efficiency measures more than others. In some cases, depending on the predictive factors some locations are supposed to invest in energy efficiency measures more than other locations, whereas in reality they are lagging. Other set of factors specific to these locations might be causing this situation. Thus, further studies are suggested looking into exploring these unexplored factors [41].

### *4.1 Life Style Analysis Approach in Industrial and Commercial Energy Efficiency Context*

As stated by Palm [46] social energy modeling approaches have been largely used in residential energy efficiency literature however there is no similar approach conducted for the industrial purposes. Accordingly, Palm [46] has attempted to find out how lifestyle categories used in residential energy efficiency literature can be adapted to industrial energy efficiency literature. Life style categories approach is stated to help understand energy culture of companies by observing perceptions, habits, and routines and in turn provide information for more accurate policies. Although sample of the study is not sufficient enough proposed categorizations regarding firms' attitudes towards energy efficiency technologies are ignorant companies, implementer of easy measures, economically interested companies and innovative environmentalists. As stated traditional market barrier researches have focused on identifying technological and economical context of the energy efficiency gap issue however, social barriers within the firms might be as important. In particular, existence of a myth like energy efficient technologies will not pay off, might be an important inhibitor however observing its existence is not possible with economical and technological approaches. Thus, studies concerning myths, established norms, values and attitudes are stated to create a different set of tools that can be utilized in categorizing SMEs. As a result, more comprehensive lifestyle analysis is suggested being conducted for industrial energy efficiency context by addressing situated knowledge, routines and behavior, how employees act in practical situations and what attitudes, norms and routines determine their actions [46]. Similar to Palm [46] a follow up research initiative has been carried out by Palm and Thollander [47] aiming to combine traditional energy efficiency diffusion approaches with social science approaches since different elements in different levels such as company, industry and policy decision maker levels that operate in different social contexts that have their own tacit knowledge, perceived truths and routines. Existence of social diversity is stated to affect companies' perception of energy efficiency measures and in turn be one of the reasons why energy efficiency gap still exists. Innovative ideas are more likely to be introduced from outside the dominant regime since traditional context prevents outside the box thinking. Thus, increasing synergy among different social networks is claimed to promote diffusion of information and energy efficient practices. Moreover, quality of information is also acclaimed to be a very important factor in adoption decisions and it is further emphasized that similar feedbacks from two different information sources can have different effects on adoption decisions and this situation can be better explained by social network context. Further research studies are suggested exploring effects of organizational perceptions on energy efficiency investments. Exploring perceptions on sustainability, costs, comfort, norms, attitudes, and routines is advised to be beneficial initially. Another worth exploring matter is stated to be mapping industrial energy regimes and exploring different existing perceptions given an energy efficiency barrier or driver with respect to different control variables [47].

## 5 Adoption Process Approach

Nair et al. [42] has attempted to survey Swedish home owners' perception on adopting building envelope energy efficiency measures. Study has been based on different phases that potential adopters may go through in adoption process. Basically, these phases have been stated as occurrence of a need for adoption, information collection and selection. In this study, each stage has been defined by related variables and influencers accordingly end users' adoption tendencies have been observed. It has been observed that although many home owners did not know about their building envelope components they were satisfied with the thermal performance, aesthetics and physical conditions. It has been stated that this situation might lead homeowners' make biased adoption decisions. Interpersonal sources and energy related service organizations have been found to be important in gathering information where as home delivered leaflets are perceived as less important. Cost items such as annual energy savings, initial costs, maintenance and functional reliability have been observed as important adoption decision variables [42].

## 6 Diffusion Models Approach

Persson et al. [48] have analyzed convergence patterns of carbon dioxide efficient technologies in iron and steel, paper, board and pulp, coal and natural gas fuelled power plants by analyzing $CO_2$ emission per output in purchasing power parity terms for 12 countries. Data has been gathered between 1980 and 1998. Energy consumption and carbon dioxide emission related indices such as SEC: Specific energy consumption [18, 77], PPI: Physical energy indicator, SE: Structural energy efficiency, TOT: Actual notational energy use in sector, SE: Sector wise carbon dioxide emission efficiency [28] have been employed in order to eliminate variances associated with country specific variables. Accordingly, diffusion of technologies have been stated to be observed better since non-technical matter variables are filtered by making use of the aforesaid indices. Accordingly, indicators have been observed to converge in each sector across the countries especially for the case of carbon dioxide efficient technologies. This is stated to imply that countries have been using similar performance level technologies more and more. It has been further stated that developing countries tend to adopt efficient technologies more than developed ones due to high energy prices [48].

# 7 Analysis of the Findings

## *7.1 Drivers Studied in Energy Efficient Technology Adoption Literature*

It is worth mentioning that there is no adoption driver specific taxonomy study in energy efficiency literature, however there is considerable amount of research efforts put towards identifying and categorizing adoption barriers. In Table 3 below you can see consolidated list of drivers for adoption of energy efficient technologies studied in the literature. Although no taxonomy study has been conducted in this study it should be noted that adoption drivers tend to vary with respect to the entity that receives the benefits resulting from positive adoption actions. First group of drivers can be explained as drivers that derive purely from personal motivations and social responsibility. For instance, Thollander et al. [68] and DeCanio [11] have shown that environmental concerns have been significant drivers for some adopters to invest in more efficient technologies even though benefits of their action do not directly return to them, but to the society in general. Drivers that have similar characteristics to aforementioned situation regarding the receiver of the benefits of positive adoption action cannot be explained by economical methods, but with behavioral models. Second group of drivers refers to the benefits such as; improved quality, reduced energy costs etc. that directly return back to the adopter as a result of their positive adoption decision. This group of drivers can be explained with economical models since adopters' actions are motivated by expectation of a benefit in return. Third group of drivers which is the

**Table 3** List of drivers for adoption of energy efficient technologies

| Drivers | References |
|---|---|
| Environmental values | [11] |
| People with ambition | [68] |
| Increasing energy price | [43] |
| Reducing energy costs | [10, 23] |
| Improving working conditions | [23] |
| Improving product quality | [23] |
| Improving company image | [10, 23, 44, 68] |
| Long term energy efficiency strategy | [23] |
| Improving compliance with regulations | [23] |
| Improving corporate environmental goals | [23] |
| Management commitment and vision | [23] |
| International and local competition | [23, 68] |
| Strategic energy efficiency plan | [23, 68] |
| Installation by public utilities | [10] |
| Fiscal arrangements | [10] |
| Subsidies | [10] |
| Niche finance opportunities | [10] |

most interesting one refers to those drivers that derive as a result of some entities' interest in capitalizing secondary entities' interests and motivations. This group of drivers seems to be between the first two groups of drivers and help internalize preuninternalized costs in the free market without requiring government intervention. For instance, improving company image by adopting more environmentally favorable technologies in order to attract more customers with environmental consciousness provides direct benefits to adopter as well as secondary entities, which are customers.

Apart from taxonomy based on the flow of benefits, a secondary taxonomy can be based on the capabilities of potential adopters, which have been studied by the researchers approaching the adoption decisions from organizational perspective. It should be noted that existence of a specific capability such as; strategic energy efficiency plan may or may not be a driver for an organization to adopt a more efficient technology, but its inexistence may be a barrier for adoption. A similar approach has also been stated by Zilahy [78] by dividing adoption motivations in two, which are namely restrictive motivation factors whose existence inhibits adoption decisions and incentive motivation factors whose existence may or may not promote adoption. From the definition given it can be implied that restrictive motivation factors derive from the interactions between organizational capability building and existing adoption barriers associated with a given energy efficient technology. As Cebon [5] also stated policy tools can be aligned either to create new capabilities for organizations to make adoption process easier or possible, or modify technologies, by addressing barriers, in order to make it possible for organizations to adopt without building new capabilities.

## 7.2 *Barriers Studied in Energy Efficient Technology Adoption Literature*

There is a considerable amount of research put towards taxonomy of energy efficiency adoption barriers. Due to generalizations by assigning adoption barriers under fewer categories it becomes hard to observe variety of adoption barriers as they appear. In Table 4 below lists of adoption barriers as they appear in the refereed papers can be found. Please note that some of barriers appear to have similar meanings, however it is beneficial to keep diversity since grouping might cause data loss. Importance of creating a list of barriers has been supported by Schleich and Gruber [56] who has suggested there is a need for more empirical research efforts in order to verify existence of the barriers found out by grounded research efforts in a given case. Thus, future empirical research papers can base their questionnaires by making use of the list as a database. By making use of the list proposed here, questionnaires can be constructed more efficiently given a region, energy efficiency technology and user type. With the help of statistical tools significance of the barriers can be identified with respect to context of the

**Table 4** List of barriers to adoption of energy efficient technologies

| Barriers | References |
|---|---|
| Access to capital | [22, 37] |
| Adjustment costs after installation | [22] |
| Adjustment costs during installation | [22] |
| Adopter firm size | [37] |
| Adopter heterogeneity | [31, 37] |
| Asymmetric information | [43, 55] |
| Auditors assessment inaccurate | [22] |
| Bad experiences in the past | [11] |
| Belief that current equipment is efficient enough | [23] |
| Belief that current installations are efficient enough | [10] |
| Belief that technology will become cheaper | [23] |
| Bounded rationality | [31, 54, 55, 56] |
| Capital subsidies | [31] |
| Community environmental impact | [31] |
| Concerns about energy efficiency investment costs and time required | [23] |
| Conflicts of interest within organization | [67, 68] |
| Contradicting codes and standards | [31, 37, 43] |
| Control and monitoring problems due to decentralization | [11] |
| Cost of identifying opportunities, analyzing cost effectiveness and tendering | [31, 67, 68] |
| Cost of staff replacement, retirement, retraining | [67] |
| Counteracting forces, trends | [37] |
| Credibility and trust | [37] |
| Demand uncertainty | [31] |
| Dependence on overall managerial performance | [11] |
| Dependency of information validity | [37] |
| Difficulties in obtaining information about the energy use of purchased equipment | [67, 68] |
| Discount/Hurdle rates | [11, 31, 54] |
| Energy costs are perceived as unimportant | [10] |
| Energy efficiency often overlooked | [22] |
| Energy objectives not integrated into operating, maintenance or purchasing procedures | [67, 68] |
| Environmental regulations | [31] |
| Existence of other prior projects | [10, 11, 67, 68, 76] |
| Geographically dispersed organization type | [54] |
| Imperfect information | [30, 31, 55, 56] |
| Imperfections in finance markets | [55] |
| Inability to measure energy consumption due to technical difficulties | [54] |
| Inadequate data and information | [73] |
| Inappropriate industrial framework | [73] |
| Inertia | [37] |
| Informal regulation | [31] |

(continued)

**Table 4** (continued)

| Barriers | References |
|---|---|
| Insufficient internal budget | [10] |
| Investments irreversible | [22] |
| Lack of access to information and knowledge | [10, 23] |
| Lack of appropriate technologies | [67, 68, 73] |
| Lack of awareness in energy saving opportunities | [73, 78] |
| Lack of coordination between government entities | [23] |
| Lack of educated manpower | [22, 67, 68, 73] |
| Lack of experience in technology and management | [73] |
| Lack of financial resources | [10, 11, 23, 67, 68, 73, 78] |
| Lack of governmental enforcement | [23] |
| Lack of incentive support | [73] |
| Lack of information about how to implement | [22] |
| Lack of internal coordination | [23] |
| Lack of management commitment | [23] |
| Lack of managerial influence | [67] |
| Lack of participation | [73] |
| Lack of staff awareness | [67, 68] |
| Lack of strategic planning | [73] |
| Lack of sub-metering | [67, 68] |
| Lack of trust in new technologies compliance with standards | [23] |
| Limited policy framework | [73] |
| Long decision chains | [67, 68] |
| Long payback periods | [11, 22] |
| Low priority given to energy management | [23, 67, 68] |
| Market structure and conditions | [31, 78] |
| Objections from different interest groups/power | [37, 73] |
| Organizational acceptance | [10] |
| Organizational culture | [37] |
| Outsourcing energy related projects due to tendency to save resources for core competencies is a new trend | [54] |
| Payoff between comfort and energy savings | [43] |
| Peer review on the technology | [10] |
| Poor information quality regarding energy efficiency opportunities | [67, 68] |
| Pricing distortions | [55] |
| Problems related to human factors | [78] |
| Quality related uncertainty | [10] |
| Rate of return too low | [22, 78] |
| Risks associated with the investments | [30, 22, 31, 37, 54, 56, 73] |
| Slim organization | [68, 67] |
| Split Incentives | [11, 22, 31, 43, 55, 56, 67] |

(continued)

**Table 4** (continued)

| Barriers | References |
|---|---|
| Taxes and permits | [31] |
| Transaction costs/Hidden costs | [30, 31, 37, 43, 55, 56] |
| Uncertainties regarding the new technology/Stochastic rate of technological progress | [10, 22, 31] |
| Uncertainty regarding the cost of production disruption/hassle/inconvenience | [22, 23, 32, 54, 67, 68, 78] |
| Uncertainty regarding the cost of the technology | [10] |
| Uncertainty regarding the future | [67, 68] |
| Uninternalized social costs | [55] |
| Use of evaluation methods (NPA, hurdle rate, IRR and such) affect the feasibility decisions-non financial investment benefits are hard to obtain | [54] |
| User culture | [37] |

case study. Accordingly, significant adoption barriers can be fed into utility energy efficiency program practices and can be used as a basis for developing new energy efficiency programs as mentioned by Thollander [70]. Having a complete list of adoption barriers associated with a technology given the important limitations, energy efficiency programs can make better determine what the efforts should be focused towards as well as better make use of available resources. Method introduced by Thollander [70] involves in employing a group of experts to identify energy efficiency adoption barriers for specified contexts such as; SMEs in Swedish industry and address identified adoption barriers by using policy tools in latter program design stages. Aforementioned methodology has been favored due to its ability to provide information for ex-ante program evaluation since it makes it possible to link adoption barriers to policy tools. Proposed method could be extended by making use of roadmapping method in order to add a time dimension into the process. Since diffusion of energy efficiency technologies is an ongoing process that happens throughout the time as well as progress of program practices attempting to address adoption barriers, use of roadmapping could provide updated information with regard to certain time points. These time points could be determined by referring to important dates that government agencies set goals for. For instance renewable energy portfolio standards provide valuable information about the goals regarding the percentage of energy generation from each available energy resources given the context and can be very useful for determining aforementioned time points. However, regarding the ex-ante program evaluation, making use of barriers and policy tools alone is important yet not enough. As mentioned by Gellings and Smith [20] demand side management practices need to be integrated into utility planning by considering the fact that depending on the demand curve feasibility of given demand side management technology such as; energy efficiency measures to be pursued may change. A complementary study that contributes to Gellings and Smith's [20] suggestions has been conducted by

Hill et al. [24] who have suggested assessing demand side management technologies by considering their potential implications on the demand curve of a given utility. A model that can incorporate all these concerns have not been studied yet although there is a few research studies available in the literature looking at the issue from different perspectives. For instance Lee et al. [34] has focused more on the project management aspect in assessing candidate technologies where as Nagesha and Balachandra [40] have employed wide range of assessment criteria to explore demand side management implementation strategies.

One of the implications that can be derived from the list is that barriers are multi dimensional. As can be observed, barriers tend to be related to behavioral, organizational, social, economical, political and many other aspects. Existence of such variety of barriers also validates why there are also multiple streams of research working in the area. An interesting observation can be mentioned is that some of the barriers appear to be existing resulting from lack of capabilities within the organizations. For instance implications from the research studies validating this finding are DeCanio's [11] work suggesting creating energy management departments in the existing organizations, Zilahy's [78] taxonomy of motivations as essentials and mediators, Cebon's [5] policy proposal towards either creating capabilities within the organizations or aligning the technologies based on organizations' needs and Kounetas et al.'s [33] work verifying that larger organizations are more successful in finding epidemic kind of information than smaller organizations. From the studies mentioned it can be understood that capability building aspect of the issue has been studied quite a bit in the literature, however authors appear to be interested in small pieces of it and use different terms. Capabilities can appear in many forms such as; existence of internal coordination, educated man power, knowledge to implement and maintain new technologies, ability to obtain information, sub-metering etc. would both help potential adopters to make sure they would succeed as a result of their positive adoption actions. With the help of previously conducted work new research initiatives can focus on explaining adoption behavior of the organizations from a capability approach. Accordingly, inspired by Zilahy [78] significance of capabilities grouped as essentials and mediators can be tested with regard to different control variables, which might either be adoption decisions or other mediators.

## *7.3 Policy Tools Studied in Energy Efficient Technology Adoption Literature*

As mentioned in the earlier section, policy tools are employed by energy efficiency programs in order to address some of the important adoption barriers that prevent energy efficient technologies from diffusing in the market at high rates. Along with that policy tools that have been studied or mentioned in the literature has also been listed as can be seen in Table 5 below. Again as stated before, this list can be used

**Table 5** List of policy tools that can be employed for promoting adoption of energy efficient technologies

| Policy Tools | References |
|---|---|
| Internal department that is dedicated to energy management for promoting improvement ideas | [11, 61] |
| Internal incentives | [11] |
| Monitor and analysis of energy use | [11] |
| Building awareness around energy conservation | [11] |
| Environmental management system | [62] |
| Electricity certification system | [67, 68] |
| Cost-based tax incentives | [23] |
| Performance-based tax incentives | [23, 71] |
| Machinery import duty exemptions | [23] |
| Accelerated depreciation | [23] |
| Energy efficiency investment subsidies | [23, 72] |
| Project demonstration | [23] |
| R&D subsidies | [23] |
| R&D dissemination | [23] |
| Information campaigns | [23] |
| Voluntary agreements | [23, 44] |
| Energy pricing | [23] |
| Industrial standards/Obligations to perform | [23, 71] |
| Energy management procedures | [61, 72] |
| Initiatives for firms to research collaboratively with universities | [61] |
| Long term energy efficiency technology policies | [61] |
| Incentives for promoting education of employees | [61] |
| White Certificates | [44] |
| Hybrid Policies | [44 |
| Promoting technologies which fit existing organizations | [5] |
| Modifying technologies to fit existing organizations | [5] |
| Support organizations which are likely to be receptive to target technologies | [5] |
| Modify organizations so that they can adapt the technology | [5] |
| Promotion through industry associations | [71] |
| Promotion through ESCOs | [71] |
| Public benefit charges | [71] |

as a reference in exploring the strategies available in designing programs as well as good feedback for future research initiatives to develop more comprehensive policy assessment models that have already been pursued to an extent [44]. One of the interesting findings from the list is that there are several policy tools that are based on collaborations between different entities. Along with that a study conducted by Thollander et al. [70] attempting to assess variables impacting energy efficiency collaborations confirms existence of an important area of research. Another interesting implication to note is that although authors such as DeCanio [11], Sola and Xavier [61] and Cebon [5] have proposed developing capabilities for organizations to make adoption processes easier however there is no practical application put forward by utilities towards these suggestions. Applicability of the proposed policy tools may be an area of study for upcoming research initiatives.

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