

**STUDY OF SELECT ISSUES IN OPERATIONAL PLANNING AND
MANAGEMENT OF SMART GRID IN INDIA**

**ARCHANA
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by

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CERTIFICATE

This is to certify that the thesis entitled “**Study of Select Issues in Operational Planning and Management of Smart Grid in India**”, being submitted by **Archana** to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy, is a bonafide record of original research work carried out by her. She has worked under our supervision and has fulfilled the requirements for the submission of the thesis, which has reached the requisite standard for the PhD degree at this institute. The results presented in this thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

Growing concerns about global warming, fossil fuel depletion, market competitiveness, and energy supply security are challenging the present electric system operation, planning, and management. As a result, there is a greater need to integrate advanced technology and distributed energy resources. Renewable resources (such as solar systems) can be put directly on the premises of residential consumers, making them into prosumers (consumers and producers of electricity). The current power grid infrastructure was not designed to meet the growing electricity demand or to accommodate the increasing integration of renewable energy sources. The existing grid features one-way communication, with supply-side changes achieving demand and supply balance. Two-way communication of electricity and data is feasible with the integration of information and communication technologies (ICT), sensors, and smart appliances with the electric grid. This grid upgradation has resulted in new market structures, services, and societal processes. Through distributed generation from solar PV and waste heat recovery, consumers can take on the new role of energy generators. Consumers might use demand response and energy storage to help the electric grid run smoothly. Technology and behaviours that empower and reassure the whole energy system, rather than just certain sections, can yield enormous economic gains. However, the development of the smart grid, which is defined as an advanced electricity network that allows two-way information and power exchange between suppliers and consumers through the widespread use of intelligent communication and management systems, is still fraught with technological, social, financial, and environmental risks, particularly in relation to social and economic factors. Not just specific technology but the overall functioning of the energy system as a socio-economic structure will be vital to the smart grid's success. As a result, the most pressing problem for policymakers over the next decade will almost certainly be the change away from a supply-driven approach to one that understands the need to integrate the many aspects and players of the energy systems. Several recent studies have identified the social component of smart grids (i.e., the participation of customers, communities, and society) as critical to the smart electrical grid's effective adoption. In this context, this thesis aims to throw light on the operational planning and management of smart grids from the perspectives of utilities, consumers, communities, and society at large, as well as to highlight and explore the major issues that it faces.

The Indian government prioritized renewable energy because it would allow the country to become self-sufficient in the energy sector. The Indian government's ambitious aim of producing 175 GW of renewable resources by 2022 has fueled a push across the country to embrace smart grid technology. The impact of these changes on power systems is enormous, necessitating the development and implementation of smart grids. With the integration of smart technologies, operational challenges have increased, so it is crucial to analyse those issues from different perspectives. This thesis also looks at how users are associated in smart grid development. The primary research question of the thesis is: what are the operational planning issues of intelligent grid technology for the energy sector in India, and what should be the strategies to deal with these issues? This research focuses on India's smart grid technology development possibilities. This research has been accomplished in three phases. Its first phase is a conceptual study in which a framework for smart grid has been proposed. The framework was developed using an integrated method of Soft-System Methodology and Fuzzy Cognitive Mapping, which includes the diverse perspectives of numerous stakeholders. The framework served as a road map for the thesis, to understand the operational and planning issues of smart grids in India. Further, an exploratory study has been performed in which various challenges related to developing and deploying of smart grid technology were studied. A total of fifty barriers to smart grid technology acceptance and adoption for consumers were listed through the literature study, and then seventeen barriers were selected after taking expert opinion. Then, using the Total Interpretive Structural Modeling (TISM) methodology, a hierarchical model was developed by identifying underlying relationships among barriers. After that, barriers were classified as the driver, dependent, linkage, and autonomous variables using MICMAC analysis.

In the second phase, barriers to smart grid technology acceptance have been ranked based on social, technical, and economic criteria. An integrated approach of AHP, PSO, FERA and EUT has been implemented to determine the ranking of barriers. Ranking of barrier showed that study of electricity consumption behaviour is important for operational planning of grid. Hence, an study was conducted to understand the electricity consumption behaviour of residential and industrial consumers. To perform this, two-year monthly consumption data (January 2019 to December 2020) of 100 residential customers and 50 industrial consumers from Kutheda village, Hamirpur, was used. Electricity consumption for different seasons and maximum electricity utilization in each season were analysed and compared. Also, consumers' yearly consumption was plotted to understand the usage flexibility. It indicates the presence of different groups of consumers whose energy usage varies differently in different seasons.

Further, K-means clustering was applied to understand the different energy behaviour of consumers and the sample size of each group. It resulted in four distinct customer groups. It also revealed a huge group of customers whose consumption is low, and their consumption patterns are not highly flexible across different seasons. Based on power consumption trends, this research will undoubtedly assist the electricity supplier in making production plans for a distinct set of users in a specific season. 15-minute interval data was also obtained from a smart grid pilot project in Kalamb, Himachal Pradesh. This data was used for weekly forecasting of electricity consumption by applying different machine-learning techniques. This analysis can be helpful in the generation, transmission and distribution planning by the central and state-level power system planning agencies by identifying areas/sectors with maximum growth. It can also provide helpful insight into the behavioural pattern of the consumer population residing in that region.

The third phase was the performance evaluation phase. The performance evaluation phase of the research is concerned with increasing the functioning of the smart grid in the electrical industry. In this phase, four smart grid pilot projects having similar functionality were studied, and industry best practices were discovered in order to improve organisational performance. A framework for the comparative study of smart grid projects was developed. Neutrosophic Analytic Hierarchy Process (N-AHP) was utilised to determine the weights of factors and sub-factors that influence smart grid performance. Neutrosophic Technique for Order of Preference by Similarity to Ideal Solution (N-TOPSIS) was used to rank smart grid development in various nations. The neutrosophic theory has been integrated with the AHP and TOPSIS to deal with complexity, ambiguity, haziness, and incomplete information.

Finally, the work concludes with a summary of the main results. This thesis adds to a deeper understanding of operational planning and management of smart grid visions. This study emphasises overarching visions with the changing role of the consumers and, lastly, overcoming challenges. A comprehensive list of barriers to smart grid technology acceptance, as well as the process of generating performance indexes, allows utilities to design a roadmap for smart grid technology deployment based on social, technical, and economic factors. The framework for the comparative study of smart grids can help utilities analyse and monitor smart grid performance in general. Customers are expected to show some flexibility by changing their energy-consumption behaviour in response to financial incentives via human or automated equipment control. This research adds to the acceptability of smart grid technologies by giving executives, managers and government officials a roadmap for the future.

सार

ग्लोबल वार्मिंग, जीवाश्म ईंधन की कमी, बाजार प्रतिस्पर्धा और ऊर्जा आपूर्ति सुरक्षा के बारे में बढ़ती चिंताओं से वर्तमान विद्युत प्रणाली संचालन, योजना और प्रबंधन को चुनौती दी जा रही है। नतीजतन, उन्नत प्रौद्योगिकी और वितरित ऊर्जा संसाधनों को एकीकृत करने की अधिक आवश्यकता है। नवीकरणीय संसाधनों (जैसे सौर प्रणाली) को सीधे आवासीय उपभोक्ताओं के परिसर में रखा जा सकता है, जिससे उन्हें उपभोक्ता (बिजली के उपभोक्ता और उत्पादक) बनाया जा सकता है। बिजली की बढ़ती मांग को पूरा करने या नवीकरणीय ऊर्जा स्रोतों के बढ़ते एकीकरण को समायोजित करने के लिए वर्तमान पावर ग्रिड इंफ्रास्ट्रक्चर को डिजाइन नहीं किया गया था। वर्तमान ग्रिड में एकतरफा संचार की सुविधा है, आपूर्ति पक्ष में बदलाव के साथ मांग और आपूर्ति संतुलन प्राप्त होता है। विद्युत ग्रिड के साथ सूचना और संचार प्रौद्योगिकी (आईसीटी), सेंसर और स्मार्ट उपकरणों के एकीकरण के साथ बिजली और डेटा का दो-तरफा संचार संभव है। इस ग्रिड उन्नयन के परिणामस्वरूप नई बाजार संरचनाएं, सेवाएं और सामाजिक प्रक्रियाएं सामने आई हैं। सौर पीवी से वितरित उत्पादन और अपशिष्ट ताप वसूली के माध्यम से, उपभोक्ता ऊर्जा जनरेटर की नई भूमिका निभाने में सक्षम होंगे। उपभोक्ता संभावित रूप से मांग प्रतिक्रिया और ऊर्जा भंडारण का उपयोग करके इलेक्ट्रिक ग्रिड को अधिक सुचारू रूप से चलाने में मदद कर सकते हैं। प्रौद्योगिकी और व्यवहार जो संपूर्ण ऊर्जा प्रणाली को सशक्त और आश्वस्त करते हैं, न कि इसके कुछ हिस्सों के बजाय, भारी आर्थिक लाभ प्राप्त कर सकते हैं। हालाँकि, स्मार्ट ग्रिड का विकास, जिसे एक उन्नत बिजली नेटवर्क के रूप में परिभाषित किया गया है, जो बुद्धिमान संचार और प्रबंधन प्रणालियों के व्यापक उपयोग के माध्यम से आपूर्तिकर्ताओं और उपभोक्ताओं के बीच दो-तरफा सूचना और बिजली विनिमय की अनुमति देता है, अभी भी तकनीकी, सामाजिक, वित्तीय से भरा हुआ है। , और पर्यावरणीय जोखिम, विशेष रूप से सामाजिक और आर्थिक कारकों के संबंध में। स्मार्ट ग्रिड की सफलता के लिए केवल विशिष्ट तकनीक ही नहीं बल्कि सामाजिक-आर्थिक संरचना के रूप में ऊर्जा प्रणाली का समग्र कामकाज महत्वपूर्ण होगा। नतीजतन, अगले दशक में नीति निर्माताओं के लिए सबसे अधिक दबाव वाली समस्या लगभग निश्चित रूप से एक आपूर्ति-संचालित दृष्टिकोण से दूर परिवर्तन होगी जो ऊर्जा प्रणालियों के कई पहलुओं और खिलाड़ियों को एकीकृत करने की आवश्यकता को समझता है। हाल के कई अध्ययनों ने स्मार्ट ग्रिड के प्रभावी अंगीकरण के लिए स्मार्ट ग्रिड के सामाजिक घटक (यानी, ग्राहकों, समुदायों और समाज की भागीदारी) को महत्वपूर्ण माना है। इस संदर्भ में, इस थीसिस का उद्देश्य उपयोगिताओं, उपभोक्ताओं, समुदायों और बड़े पैमाने पर समाज के दृष्टिकोण से स्मार्ट ग्रिड की

परिचालन योजना और प्रबंधन पर प्रकाश डालना है, साथ ही उन प्रमुख मुद्दों को उजागर करना और उनका पता लगाना है जिनका सामना करना पड़ता है। .

भारत सरकार ने अक्षय ऊर्जा को प्राथमिकता दी है क्योंकि यह देश को ऊर्जा क्षेत्र में आत्मनिर्भर बनने की अनुमति देगा। 2022 तक 175 GW नवीकरणीय संसाधनों का उत्पादन करने के भारत सरकार के महत्वाकांक्षी लक्ष्य ने देश भर में स्मार्ट ग्रिड प्रौद्योगिकी को अपनाने के लिए प्रेरित किया है। बिजली प्रणालियों पर इन परिवर्तनों का प्रभाव बहुत अधिक है, जिससे स्मार्ट ग्रिड के विकास और कार्यान्वयन की आवश्यकता होती है। स्मार्ट तकनीकों के एकीकरण के साथ, परिचालन संबंधी चुनौतियाँ बढ़ गई हैं, इसलिए उन मुद्दों का विभिन्न दृष्टिकोणों से विश्लेषण करना महत्वपूर्ण है। यह थीसिस यह भी देखती है कि कैसे उपभोक्ता स्मार्ट ग्रिड के विकास में शामिल होते हैं। थीसिस का प्राथमिक शोध प्रश्न है: भारत में बिजली क्षेत्र के लिए स्मार्ट ग्रिड प्रौद्योगिकी की परिचालन योजना के मुद्दे क्या हैं और इन मुद्दों से निपटने के लिए क्या रणनीति होनी चाहिए? यह शोध भारत की स्मार्ट ग्रिड प्रौद्योगिकी विकास संभावनाओं पर केंद्रित है। यह कार्य तीन चरणों में किया गया है। पहला चरण वैचारिक अध्ययन है जिसमें स्मार्ट ग्रिड के लिए एक रूपरेखा प्रस्तावित की गई है। सॉफ्ट-सिस्टम मेथडोलॉजी और फ़ज़ी कॉग्निटिव मैपिंग की एक एकीकृत पद्धति का उपयोग करके रूपरेखा विकसित की गई थी, जिसमें कई हितधारकों के विविध दृष्टिकोण शामिल हैं। भारत में स्मार्ट ग्रिड के परिचालन और योजना संबंधी मुद्दों को समझने के लक्ष्य के साथ थीसिस के लिए एक रोड मैप के रूप में कार्य किया गया। इसके अलावा, एक खोजपूर्ण अध्ययन किया गया है जिसमें स्मार्ट ग्रिड प्रौद्योगिकी के विकास और परिनियोजन से संबंधित विभिन्न चुनौतियों का अध्ययन किया गया। साहित्य अध्ययन के माध्यम से उपभोक्ताओं के लिए स्मार्ट ग्रिड प्रौद्योगिकी स्वीकृति और अपनाने के लिए कुल पचास बाधाओं को सूचीबद्ध किया गया था, और फिर विशेषज्ञ राय लेने के बाद सत्रह बाधाओं का चयन किया गया था। फिर, टोटल इंटरप्रिटिव स्ट्रक्चरल मॉडलिंग (TISM) पद्धति का उपयोग करते हुए, बाधाओं के बीच अंतर्निहित संबंधों की पहचान करके एक पदानुक्रमित मॉडल विकसित किया गया। उसके बाद, MICMAC विश्लेषण का उपयोग करके बाधाओं को चालक, आश्रित, लिंकेज और स्वायत्त चर के रूप में वर्गीकृत किया गया था।

दूसरे चरण में, सामाजिक, तकनीकी और आर्थिक मानदंडों के आधार पर स्मार्ट ग्रिड प्रौद्योगिकी स्वीकृति की बाधाओं को स्थान दिया गया है। बाधाओं की रैंकिंग निर्धारित करने के लिए AHP, PSO, FERA और EUT का एक एकीकृत दृष्टिकोण लागू किया गया है। बैरियर की रैंकिंग से पता चलता है कि ग्रिड की परिचालन योजना के लिए बिजली खपत व्यवहार का अध्ययन महत्वपूर्ण है। इसलिए, आवासीय और औद्योगिक उपभोक्ताओं के बिजली खपत व्यवहार को समझने के लिए एक अध्ययन किया गया। इसे करने के लिए, हमीरपुर के कुठेड़ा गांव के 100 आवासीय ग्राहकों और 50 औद्योगिक उपभोक्ताओं

के दो साल के मासिक खपत डेटा (जनवरी 2019 से दिसंबर 2020) का उपयोग किया गया था। विभिन्न मौसमों के लिए बिजली की खपत और प्रत्येक मौसम में बिजली के अधिकतम उपयोग का विश्लेषण और तुलना की गई। इसके अलावा, उपभोक्ताओं की वार्षिक खपत को उपयोग के लचीलेपन को समझने के लिए प्लॉट किया गया था। यह उपभोक्ताओं के विभिन्न समूहों की उपस्थिति को इंगित करता है जिनकी ऊर्जा खपत अलग-अलग मौसमों में अलग-अलग होती है। इसके अलावा, के-मीन्स क्लस्टरिंग को उपभोक्ताओं के विभिन्न ऊर्जा व्यवहार और प्रत्येक समूह के नमूना आकार को समझने के लिए लागू किया गया था। इसके परिणामस्वरूप चार अलग-अलग ग्राहक समूह बन गए। यह भी पता चला कि ग्राहकों का एक बड़ा समूह है जिनकी खपत कम है, और विभिन्न 'मौसमों' में उनके उपभोग के पैटर्न अत्यधिक लचीले नहीं हैं। बिजली की खपत के रुझान के आधार पर, यह शोध निश्चित मौसम में उपयोगकर्ताओं के एक अलग समूह के लिए उत्पादन योजना बनाने में निस्संदेह बिजली आपूर्तिकर्ता की सहायता करेगा। हिमाचल प्रदेश के कलंब में एक स्मार्ट ग्रिड पायलट प्रोजेक्ट से 15 मिनट के अंतराल का डेटा भी प्राप्त किया गया था। इस डेटा का उपयोग विभिन्न मशीन-लर्निंग तकनीकों को लागू करके बिजली की खपत के साप्ताहिक पूर्वानुमान के लिए किया गया था। यह विश्लेषण अधिकतम विकास वाले क्षेत्रों/क्षेत्रों की पहचान करके केंद्रीय और राज्य स्तर की बिजली व्यवस्था योजना एजेंसियों द्वारा उत्पादन, पारेषण और वितरण योजना में सहायक हो सकता है। यह उस क्षेत्र में रहने वाले उपभोक्ता आबादी के व्यवहार पैटर्न में उपयोगी अंतर्दृष्टि भी प्रदान कर सकता है।

तीसरा चरण प्रदर्शन मूल्यांकन चरण था। अनुसंधान का प्रदर्शन मूल्यांकन चरण विद्युत उद्योग में स्मार्ट ग्रिड के कामकाज को बढ़ाने से संबंधित है। इस चरण में, समान कार्यक्षमता वाली चार स्मार्ट ग्रिड पायलट परियोजनाओं का अध्ययन किया गया और संगठनात्मक प्रदर्शन को बेहतर बनाने के लिए उद्योग की सर्वोत्तम प्रथाओं की खोज की गई। स्मार्ट ग्रिड परियोजनाओं के तुलनात्मक अध्ययन के लिए एक रूपरेखा विकसित की गई। स्मार्ट ग्रिड प्रदर्शन को प्रभावित करने वाले कारकों और उप-कारकों के भार को निर्धारित करने के लिए न्यूट्रोसोफिक विश्लेषणात्मक पदानुक्रम प्रक्रिया (एन-एएचपी) का उपयोग किया गया था। विभिन्न देशों में स्मार्ट ग्रिड विकास को रैंक करने के लिए आदर्श समाधान (N-TOPSIS) की समानता द्वारा प्राथमिकता के क्रम के लिए न्यूट्रोसोफिक तकनीक का उपयोग किया गया था। जटिलता, अस्पष्टता, अस्पष्टता और अधूरी जानकारी से निपटने के लिए न्यूट्रोसोफिक सिद्धांत को AHP और TOPSIS के साथ एकीकृत किया गया है।

अंत में, कार्य मुख्य परिणामों के सारांश के साथ समाप्त होता है। यह थीसिस स्मार्ट ग्रिड विजन की परिचालन योजना और प्रबंधन की गहरी समझ को जोड़ती है। यह अध्ययन उपभोक्ताओं की बदलती भूमिका और अंत में, चुनौतियों पर काबू पाने के साथ व्यापक दृष्टिकोण पर जोर देता है। स्मार्ट ग्रिड

प्रौद्योगिकी स्वीकृति के लिए बाधाओं की एक व्यापक सूची, साथ ही प्रदर्शन सूचकांक उत्पन्न करने की प्रक्रिया, उपयोगिताओं को सामाजिक, तकनीकी और आर्थिक कारकों के आधार पर स्मार्ट ग्रिड प्रौद्योगिकी परिनियोजन के लिए एक रोडमैप डिजाइन करने की अनुमति देती है। स्मार्ट ग्रिड के तुलनात्मक अध्ययन के लिए रूपरेखा उपयोगिताओं को सामान्य रूप से स्मार्ट ग्रिड के प्रदर्शन का विश्लेषण और निगरानी करने में मदद कर सकती है। ग्राहकों से अपेक्षा की जाती है कि वे मानव या स्वचालित उपकरण नियंत्रण के माध्यम से वित्तीय प्रोत्साहनों के जवाब में अपने ऊर्जा-खपत व्यवहार को बदलकर कुछ लचीलापन दिखाएँ। यह शोध अधिकारियों, प्रबंधकों और सरकारी अधिकारियों को भविष्य के लिए एक रोडमैप देकर स्मार्ट ग्रिड प्रौद्योगिकियों की स्वीकार्यता को बढ़ाता है।

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
Abstract	iii
सार	vii
List of figures	xix
List of tables	xxiii
List of abbreviations	xxvii
Chapter 1 Introduction to the study	1
1.1 Overview	1
1.2 Introduction	1
1.3 Development of smart grid – Background of the study	2
1.4 Planning and operations of smart grid	3
1.5 Motivation of research	6
1.6 Research questions and objectives	7
1.7 Significance of the study	8
1.8 Scope of study	8
1.9 Proposed methodology	8
1.10 Organization of the thesis.....	10
1.11 Chapter summary	13
Chapter 2 Research background	15
2.1 Overview	15
2.2 Introduction	15
2.3 2012 Blackout in India	17
2.3.1 Reason of blackout	17
2.3.2 After effect of blackout.....	18
2.4 Need of smart grid.....	19
2.5 PESTEL analysis.....	20
2.6 Chapter summary	25
Chapter 3 Literature review on smart grid	27
3.1 Overview	27
3.2 Introduction	27
3.3 The search process for the literature review.....	27

3.3.1 Data extraction.....	29
3.3.2 Inclusion and exclusion criteria.....	29
3.3.3 Data analysis and synthesis	30
3.4 Findings based on descriptive analysis for smart grid	32
3.4.1 Year wise publication trend of smart grid articles.....	32
3.4.2 Journal wise distribution of research papers.....	32
3.4.3 Author wise distribution	33
3.4.4 Country-wise distribution of research papers	33
3.5 Literature review analysis of smart grid.....	34
3.6 Evolution of electric grid (Theme 1).....	35
3.6.1 Components of the electric grid.....	36
3.6.2 Factors affecting the performance of the existing grid and the need for a smart grid	37
3.7 Development of smart grid (Theme 2).....	39
3.7.1 Definition of smart grid	41
3.7.2 Conceptual model of smart grid technology.....	42
3.7.3 Environmental ramifications	45
3.7.4 Reliability of smart grid.....	47
3.7.5 Benefits of smart grid	47
3.7.6 Key Challenges of smart grid	50
3.8 Operational planning and management of smart grid (Theme 3)	50
3.8.1 Storage of energy	51
3.8.2 Electric vehicle	53
3.8.3 Distributed generation	54
3.8.4 Security.....	55
3.8.5 Demand response.....	56
3.8.6 Deployment of smart technologies and smart devices	57
3.8.7 Interoperability	58
3.8.8 Control and communication	59
3.8.9 Sensing, measurement and Internet of things.....	60
3.8.10 Simulators and information systems.....	62
3.9 Smart grid technology acceptance (Theme 4).....	62
3.9.1 Technology acceptance theories.....	63
3.10 Research gaps.....	75

3.11 Chapter Summary.....	77
Chapter 4 Research Design and Methodology	79
4.1 Overview	79
4.2 Introduction	79
4.3 Research design.....	79
4.4 Research methodologies.....	80
4.4.1 Justification for mixed method.....	80
4.4.2 Questionnaire design and administration	81
4.5 Soft system methodology (SSM)	82
4.6 Fuzzy cognitive mapping (FCM)	84
4.7 Mental modeler software.....	86
4.8 Exploratory factor analysis (EFA)	87
4.9 Total interpretative structural modelling (TISM).....	87
4.9.1 Steps of TISM methodology.....	88
4.10 Structural equation modelling (SEM)	89
4.10.1 Data validity test.....	91
4.11 Analytical hierarchy process	91
4.12 Evidential reasoning algorithm (ERA).....	93
4.13 Particle swarm optimization.....	96
4.14 Hierarchical clustering	97
4.15 PESTEL analysis.....	97
4.16 Neutrosophic AHP	98
4.17 TOPSIS.....	100
4.18 K-Means algorithm	100
4.19 Linear regression	101
4.19.1 Types of linear regression.....	101
4.19.2 Finding the best fit line.....	102
4.19.3 Cost function.....	102
4.19.4 Model performance.....	102
4.19.5 Regularization.....	103
4.19.6 Assumptions of linear regression	103
4.20 Least absolute shrinkage and selection operator (LASSO) regression	103
4.21 Ridge Regression (L2 regularization)	104

4.22 Elastic net	104
4.23 Gradient descent.....	104
4.24 Mapping of research objectives to research methodologies.....	104
4.25 Justification for employing different research methodologies catering to each research objectives.....	105
4.25.1 Soft system methodology for research objective one (RO1).....	105
4.25.2 An integrated approach based on questionnaire survey, TISM and SEM methodologies for research objective two (RO2).....	105
4.25.3 Use of K-Means clustering and linear regression for research objective three (RO3).....	107
4.25.4 An integrated approach based on Hierarchical clustering, Neutrosophic AHP, and Neutrosophic TOPSIS for research objective four (RO4).....	107
4.25.5 An integrated approach of fuzzy evidential reasoning algorithm and particle swarm optimization for research objective five (RO5)	107
4.26 Chapter summary	108
Chapter 5 Development of smart grid for the power sector in India.....	109
5.1 Overview	109
5.2 Introduction.....	109
5.3 Application of Soft system methodology.....	111
5.3.1 Step 1: Problem situation.....	111
5.4 Phase 1.....	115
5.4.1 Step 2: Rich picture	115
5.4.2 Step 3: Root definition.....	119
5.4.3 Step 4: Conceptual model.....	122
5.4.4 Step 5: Comparison with real world	129
5.4.5 Step 6: Making interventions.....	131
5.4.6 Stage 7: Action to improve the situation	131
5.5 Phase 2 of problem description	136
5.5.1 Step 2: Rich picture	136
5.5.2 Step 3: Root definition.....	142
5.5.3 Step 4: Conceptual model.....	143
5.5.4 Step 5: Comparison with real world	144
5.5.5 Step 6: Making interventions.....	145
5.5.6 Stage 7: Action to improve the situation	146
5.6 Conclusion.....	147

5.7	Limitations of the present study	149
5.8	Chapter summary	149
Chapter 6 Modelling barriers for smart grid technology acceptance in India		151
6.1	Overview	151
6.2	Introduction	151
6.3	Research framework.....	152
6.4	Identification of barriers.....	152
6.4.1	Questionnaire development	153
6.4.2	Analysis of EFA result	166
6.4.3	TISM model.....	168
6.4.4	Analysis of TISM based model	169
6.5	Classification of barriers: MICMAC analysis.....	179
6.6	Discussion	181
6.6.1	Proposed solutions for managing the barriers	182
6.7	Validation of the TISM model	183
6.7.1	Model validation.....	183
6.7.2	Data validity test.....	184
6.7.3	Measurement model validity	186
6.7.4	Structural model validity	189
6.8	Implications of the research	192
6.8.1	Managerial relevance.....	194
6.8.2	Practical implications	194
6.9	Chapter summary	195
Chapter 7 Using evidential reasoning approach for prioritization of barriers for smart grid technology acceptance in India.....		197
7.1	Overview	197
7.2	Introduction	197
7.3	Research framework.....	198
7.4	Barriers to smart grid technology acceptance	198
7.4.1	Role of technical criterion in smart grid technology acceptance.....	200
7.4.2	Role of social criterion in smart grid technology acceptance.....	200
7.4.3	Role of economic criterion in smart grid technology acceptance	201
7.5	Implementation of AHP to calculate the weight of each criterion.....	201
7.5.1	Data collection and pre-processing.....	201

7.5.2 Implementation of AHP and PSO	201
7.6 Implementation of FERA	204
7.6.1 Constructing a survey based on criteria in the lowest level	204
7.6.2 Calculation of belief degree.....	204
7.6.3 Calculation of rank with respect to all criteria with IDS software	205
7.7 Results and discussions	208
7.7.1 Analysis of technical criteria	210
7.7.2 Analysis of social criteria	210
7.7.3 Analysis of economic criteria	211
7.8 Sensitivity analysis.....	212
7.9 Managerial implications.....	214
7.10 Chapter summary	216
Chapter 8 Investigating electricity usage profile for residential and industrial consumers in India.....	217
8.1 Overview	217
8.2 Introduction	217
8.3 Analysis of electricity consumption pattern of residential consumers.....	219
8.3.1 Data-set.....	219
8.3.2 Results	220
8.3.3 Data Visualization	220
8.3.4 Yearly profiles	221
8.3.5 Consumer segmentation	223
8.4 Analysis of consumption pattern of industrial consumers	225
8.5 Daily electricity consumption analysis and weekly forecast	227
8.6 Daily curve load	231
8.7 Application of machine learning algorithm	231
8.8 Discussion	233
8.9 Chapter summary	233
Chapter 9 A framework for comparative study of smart grid projects: Lessons learnt and best practices.....	235
9.1 Overview	235
9.2 Introduction	235
9.3 Research framework.....	237
9.4 Framework for comparative study of smart grid projects	237

9.4.1 Data collection	237
9.4.2 Factors identification: Hierarchical clustering	239
9.5 Empirical analysis	244
9.5.1 Determination of weight of factors and sub-factors: Application of Neutrosophic AHP	247
9.5.2 Ranking of alternatives: Application of TOPSIS	254
9.6 Sensitivity analysis	260
9.7 Discussion	261
9.8 Lessons learnt and the best practices.....	262
9.9 Chapter summary	263
Chapter 10 Summary of research findings and conclusion	265
10.1 Overview	265
10.2 Introduction	265
10.2.1 Conceptual study	266
10.2.2 Case study.....	267
10.2.3 Empirical analysis.....	268
10.3 Major recommendations.....	268
10.3.1 Recommendations for corporate managers	269
10.3.2 Recommendations for analysts and decision-makers.....	269
10.3.3 Recommendations for utilities.....	270
10.4 Implications.....	270
10.5 Significant contributions to research.....	273
10.6 Limitations of the study.....	273
10.7 Directions for future research.....	274
10.8 Concluding observations.....	274
References.....	277
Appendix.....	305
Appendix A	305
Appendix B	309
Appendix C.....	313
Appendix D.....	315
Biosketch of the Author.....	319

LIST OF FIGURES

Figure 1.1: Block diagram of smart grid.....	2
Figure 1.2: Typical all-India load curve (source: POSOCO report 2016).....	4
Figure 1.3: Percentage of electric consumption by various sectors (source: POSOCO report 2016)	5
Figure 1.4: Research design	11
Figure 1.5: Organization of the thesis	12
Figure 3.1: Articles search process for literature review	28
Figure 3.2: Year wise publication pattern on smart grid research articles.....	32
Figure 3.3: World cloud.....	35
Figure 3.4: Components of the electric grid	37
Figure 3.5: Basic electric setup.....	38
Figure 3.6: Interaction of actors in different smart grid domains by NIST	44
Figure 3.7: Theory of Reasoned Action (M. Fishbein & Ajzen, 1975).....	64
Figure 3.8: The Theory of Planned Behaviour (Ajzen, 1991)	64
Figure 3.9: Original TAM model (Davis, 1985).....	65
Figure 3.10: First modified version of the Technology Acceptance Model (TAM) (Davis et al., 1989)	66
Figure 3.11: Final version of the Technology Acceptance Model (TAM) (Davis & Venkatesh, 1996)	66
Figure 3.12: Technology Acceptance Model (TAM2) (Venkatesh & Davis, 2000)	67
Figure 3.13: Technology Acceptance Model 3 (TAM3) (Venkatesh et al., 2003).....	69
Figure 4.1: Flow chart of the research	81
Figure 4.2: SSM methodology adapted from Checkland and Scholes (2003).....	83
Figure 4.3: (a) Structural model and (b) Measurement model	90
Figure 4.4: Hierarchical structure for AHP.....	92
Figure 4.5: Triangular fuzzy numbers	95
Figure 4.6: Fuzzy triangular membership function.....	95
Figure 4.7: Conversion of fuzzy ratings to five non-normalized grades	96
Figure 5.1: Process of data collection	112
Figure 5.2: Symptoms map	118
Figure 5.3: Rich picture	119

Figure 5.4: Pareto analysis.....	120
Figure 5.5: A visual representation of the developed FCMs. Positive links are depicted in blue colour, and negative links are depicted in red colour	124
Figure 5.6: Worst case scenario	125
Figure 5.7: Best case scenario.....	126
Figure 5.8: Best case scenario (only government support).....	126
Figure 5.9: Best case scenario (only technical support)	127
Figure 5.10: Best case scenario with (only consumer support)	127
Figure 5.11: Initial Conceptual model	128
Figure 5.12: Developed final Conceptual model for smart grid technology	132
Figure 5.13: Smart grid framework	139
Figure 5.14: Rich picture	140
Figure 5.15: Pareto analysis.....	141
Figure 5.16: Conceptual model.....	144
Figure 5.17: Final implementable mode.....	148
Figure 6.1: Research framework.....	154
Figure 6.2: TISM based hierarchical model for barriers in smart grid technology adoption	173
Figure 6.3: TISM-based hierarchical model with factors representing TAM, RBV and institutional theory	180
Figure 6.4: Driving power and dependence power diagram.....	181
Figure 6.5: Path diagram.....	185
Figure 6.6: TISM based hierarchical model for smart grid technology acceptance	193
Figure 7.1: The Research framework.....	199
Figure 7.2: Hierarchical structure of the problem.....	202
Figure 7.3: PSO output in Jupyter notebook.....	204
Figure 7.4: Main window of IDS software	206
Figure 7.5: Value of belief degree fed in the software	206
Figure 7.6: Weight assigned to each criterion in the software.....	208
Figure 7.7: Sensitivity analysis	213
Figure 8.1: Data set after aggregating consumption for seasons	219
Figure 8.2: Data set after aggregating consumption for seasons	221
Figure 8.3: Data visualization for the month of winter, summer and monsoon	222
Figure 8.4: Electricity consumption pattern of 100 consumers	223
Figure 8.5: Elbow method graph	224

Figure 8.6: Four groups of consumers on the basis of electricity consumption behaviour ...	224
Figure 8.7: Monthly electricity consumption data of industrial consumers	226
Figure 8.8: Electricity consumption of industrial consumers in different seasons	226
Figure 8.9: Yearly consumption profile of industrial consumers	227
Figure 8.10: Daily consumption data of residential consumer	228
Figure 8.11: Daily demand curve.....	231
Figure 8.12: Plot of RMSE score for each day of the week	232
Figure 9.1: The three-phase research framework	238
Figure 9.2: Main window of KH Coder software	239
Figure 9.3: Clusters of keywords formed on applying hierarchical clustering in KHCoder .	240
Figure 9.4: Formation of factors from keyword clusters	241
Figure 9.5: A comparative study framework for performance evaluation of the smart grid .	244
Figure 9.6: Sensitivity analysis.....	261

LIST OF TABLES

Table 1.1: Research objectives and methodology.....	9
Table 2.1: PESTEL analysis of smart grid technology for India.....	21
Table 2.2: PESTEL analysis of smart grid technology for the USA	24
Table 3.1: The proposed systematic search	31
Table 3.2: Classification of articles	31
Table 3.3: Top fourteen journals in the area of smart grid	33
Table 3.4: Top ten authors contributing in the area of smart grid	34
Table 3.5: Geographical distribution of research papers	34
Table 3.6: The traditional electric grid versus the smart grid	42
Table 3.7: Domains in the conceptual model of smart grid.....	43
Table 3.8: Analogy between the internet and evolving smart grid.....	45
Table 4.1: Elements and definition of CATWOE.....	83
Table 4.2: Inference rule for FCM.....	85
Table 4.3: Threshold function used in FCM.....	86
Table 4.4: Used performance measures and targets to validate the measurement model.....	92
Table 4.5: Random consistency index	93
Table 4.6: Linguistic terms with fuzzy values and notations.....	96
Table 4.7: Mapping research objectives to research methodologies	106
Table 5.1: Profile of experts who participated in interview and workshop.....	113
Table 5.2: Themes and code words identified through the analysis of interview transcripts	114
Table 5.3: Mapping of conflict areas to identify root causes.....	116
Table 5.4: Various perspectives identified for smart grid development.....	120
Table 5.5: CATWOE analysis for the perspective infrastructure development.	120
Table 5.6: CATWOE analysis for the perspective consumer's attitude.....	121
Table 5.7: CATWOE analysis for the perspective renewable energy integration.....	121
Table 5.8: Factors identified in the FCM workshop.....	124
Table 5.9: Comparison of the conceptual world with real world	133
Table 5.10: Mapping of conflict areas to identify root causes.....	138
Table 5.11: Various perspectives identified for smart grid development.....	141
Table 5.12: CATOWE analysis	142
Table 6.1: Identified factors for smart grid technology acceptance with references	155

Table 6.2: List of barriers for smart grid technology acceptance	156
Table 6.3: Profile of experts who participated in the semi-structured interview.....	164
Table 6.4: Sample questionnaire.....	164
Table 6.5: Sample data collected by questionnaire survey	164
Table 6.6: Questions for the semi-structured interview.....	164
Table 6.7: Modified list of barriers to smart grid technology acceptance	165
Table 6.8: KMO and Bartlett's Test value and reliability statistics	167
Table 6.9: KMO and Bartlett's Test value for 16 variables	167
Table 6.10: Result of EFA for 16 variables	168
Table 6.11: Initial reachability matrix for barriers to adopting smart grid technologies.....	169
Table 6.12: Final reachability matrix for barriers	170
Table 6.13: Partitioning of the reachability matrix into different levels.....	171
Table 6.14: Demographics of the included respondents.....	186
Table 6.15: Survey constructs.....	187
Table 6.16: Composite reliability measures of latent variables with more than one observed variable.....	189
Table 6.17: Average Variance Extracted (AVE)	190
Table 6.18: Table of squared correlation and AVEs.....	191
Table 6.19: Model fit indices	192
Table 7.1: Barriers to customer acceptance for smart grid	200
Table 7.2: Questionnaire form to facilitate the comparison of criteria with respect to the goal	203
Table 7.3: Pairwise comparison matrix from expert opinion and C.R. ratio	203
Table 7.4: Sample questionnaire survey to assess the factors under each criterion	205
Table 7.5: Expert's opinion on each criterion.....	205
Table 7.6: Average of expert's opinion and belief degrees of variable	207
Table 7.7: Rank of the barriers for different criteria.....	209
Table 7.8: Sensitivity analysis	213
Table 8.1: Consumption characteristics of four groups of consumers.....	225
Table 8.2: RMSE score for each day of the week.....	232
Table 9.1: List of factors and sub-factors for benchmarking of smart grid technology	242
Table 9.2: Description of selected sub-factors.....	243
Table 9.3: Details of the selected smart grid projects	245
Table 9.4: Linguistic variables and importance weight based on neutrosophic values	248

Table 9.5: Pairwise comparison matrix for calculation of the weight of factors	248
Table 9.6: Crisp value for pairwise comparison matrix.....	249
Table 9.7: Pairwise comparison matrix of sub-factors with respect to factors F2.....	249
Table 9.8: Crisp value of pairwise comparison matrix of sub-factors with respect to factors F2	249
Table 9.9: Pairwise comparison matrix of sub-factors with respect to factors F3.....	250
Table 9.10: Crisp value of pairwise comparison matrix of sub-factors with respect to factors F3	250
Table 9.11: Pairwise comparison matrix of sub-factors with respect to factors F5.....	250
Table 9.12: Crisp value of pairwise comparison matrix of sub-factors with respect to factors F5	250
Table 9.13: Pairwise comparison matrix of sub-factors with respect to factors F6.....	251
Table 9.14: Crisp value of pairwise comparison matrix of sub-factors with respect to factors F6	251
Table 9.15: List of factors and sub-factors for evaluation of smart grid	251
Table 9.16: Neutrosophic decision matrix	256
Table 9.17: Rank calculation by TOPSIS	257
Table 9.18: Rank calculation by TOPSIS under evaluation criteria Benefits to consumers .	258
Table 9.19: Evaluation under the criteria: Benefits to utilities	259
Table 9.20: Ranking of different smart grid projects.....	260
Table 9.21: Sensitivity analysis	261

LIST OF ABBREVIATIONS

AMI	Advanced metering infrastructure
AT&C	Aggregate technical and commercial losses
AT&D	Aggregate transmission and distribution loss
BESS	Battery energy storage system
CEA	Central electricity authority
CERC	Central electricity regulatory commission
DA	Distribution automation
DER	Distributed energy resources
DLC	Direct load control
DMS	Distribution management system
DoS	Denial of service
DR	Demand response
DRMS	Demand response management system
DSO	Distribution system operators
DST	Department of science and technology
DSM	Demand-side management
DTMS	Distribution transformer management system
DTR	Dynamic thermal rating
DTMU	Distribution transformer monitoring unit
EFA	Exploratory factor analysis
EMI	Electromagnetic interference
EMS	Energy management system
ERP	Enterprise resource planning
EV	Electric vehicle
EVCI	Electric vehicle charging infrastructure
FCM	Fuzzy cognitive method
GHG	Greenhouse gas
GIS	Geographical information system
GoI	Government of India
GPS	Global positioning system

HAN	Home area network
ICT	Information and communication technology
IDS	Intrusion detection system
IED	Intelligent electronic devices
IEEE	Institute of electrical and electronics engineers
ISGF	India smart grid forum
ISGTF	India smart grid task force
IoT	Internet of things
IP	Internet protocol
IT	Information technology
KMO	Kaiser-Meyer-Olkin
kWh	Kilowatt-hour
LAN	Local area network
MDMS	Meter data management system
MG/DG	Microgrid/Distributed generation
MICMAC	Matrice d'impacts croisés multiplication appliquée à un classment
MoP	Ministry of power
NCIIPC	National critical information infrastructure protection centre
NIST	National institute of standards and technology
NSGM	National smart grid mission
OMS	Outage management system
O&M	Operating and maintenance
PLM	Peak load management
PMUs	Phase measurement units
PQ	Power quality
PQM	Power quality management
PV	Rooftop photovoltaic
SA	Substation automation
SCADA	Supervisory control and data acquisition
SMPS	Switch-mode power supplies
SSM	Soft system methodology

RTU	Remote terminal unit
T&D	Transmission and distribution
TAM	Technology acceptance model
TISM	Total interpretive structural modelling
TOU	Time of use
WAMS	Wide area management system
WAN	Wide area network