A

DISSERTATION REPORT

on

OPTIMAL ELECTRICITY PROCUREMENT FOR INDIAN LARGE CONSUMER CONSIDERING UNCERTAINTIES

Submitted in partial fulfilment for the award of the degree of

Master of Technology in Renewable Engineering

by

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CERTIFICATE

This is certified that the dissertation report entitled **"OPTIMAL ELECTRICITY PROCUREMENT FOR INDIAN LARGE CONSUMER CONSIDERING UNCERTAINTIES"** prepared by **POOJA SHARMA** (ID-2014PCV5097), in the partial fulfilment of the award of the Degree **Master of Technology** in **Renewable Engineering** of Malaviya National Institute of Technology Jaipur is a record of bonafide research work carried out by her under my supervision and is hereby approved for submission. The contents of this dissertation work, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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I **POOJA SHARMA** hereby declare that the dissertation entitled **"OPTIMAL ELECTRICITY PROCUREMENT FOR INDIAN LARGE CONSUMER CONSIDERING UNCERTAINTIES "** being submitted by me in partial fulfilment of the degree of **M. Tech (Renewable Engineering)** is a research work carried out by me under the supervision of **Dr. Urmila Brighu,** and under the co-supervision of **Dr. Parul Mathuria** and the contents of this dissertation work, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma. I also certify that no part of this dissertation work has been copied or borrowed from anyone else. In case any type of plagiarism is found out, I will be solely and completely responsible for it.

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ABSTRACT

During last two decades, Indian power sector is going through a lot of reforms for healthy market competition and promotion of renewable energy. Open access is a major power sector reform in generation deficit India and encourages short-term trading for meeting variations in demand. An open access large consumer in India can participate in short term trading through bilateral contracts; Power Exchanges (PXs) or Unscheduled Interchange (UI) transactions. Besides, it needs to satisfy obligations of renewable purchase. UI mechanism has emerged as a powerful tool for maintaining grid discipline, penalizing the market entities for causing the real time deviations in direction to grid imbalances. A buyer pays UI charges for over-withdrawal of power more than the scheduled power at unhealthy grid frequency. Prices of PX's Day Ahead Market (DAM) are uncertain, while UI charges for frequency variations vary widely due to real-time power shortages. Facing these market conditions, this work proposes an optimal short-term power procurement strategy for a large consumer, from available trading options. Small self-generation facility and demand flexibility have also been considered.

This thesis models the consumption scheduling problem of Indian open access consumers. A practical case study of Indian open access consumer has been done considering two cases. The first case proposes optimal short term planning model for a large consumer while considering uncertainty of DAM price and UI rate. This model is applicable to any open access industry consumer who is trading in the wholesale markets (PXs) but not big enough for impacting the frequency of Indian grid. On the other hand, the second case considers the problem of distribution companies or large industries of India, shares a large portion of system demand and impact grid frequency. In the second case, UI rate has been calculated from the grid frequency depending upon the grid conditions. In this short term planning model, multimarket DAM uncertainties have been modeled and consumption scheduling is done by flexible loads for obtaining optimal consumption schedules. For both the cases, mean-variance optimization approach has been considered in order to get optimum trade-off between minimum cost and risk. Both mathematical models have been optimized by General Algebraic Mathematical System (GAMS).

Conclusive results are produced for the consumer according to its preferences and present scenario. Obtained results represent that consumer can shift its demand in order to get minimum cost. Real time grid balancing can also be achieved by the consumer using the planning model such that grid frequency can be improved.

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ABBREVIATIONS

Symbol	Description
ABT	Availability Based Tariff
AD	Accelerated Depreciation
AGC	Automated Generation Control
APDRP	Accelerated Power Development and Reform programme
AT&C	Aggregate Technical and Commercial Loss
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CPP	Captive Power Producers
CVaR	Conditional value-at-risk
DAM	Day Ahead Market
DSM	Deviation Settlement Mechanism
FiT	Feed in Tariff
GAMS	General Algebraic Modelling System
GBI	Generation Based Incentives
GRG	Generalised Reduced Gradient
IEGC	Indian Electricity Grid Code
IEX	Indian Energy Exchange
IGDT	Information Gap Decision Theory
IPP	Independent Power Producers
ISTL	Inter State Trading Licensee
JNNSM	Jawaharlal Nehru National Solar Mission
MCP	Market Clearing Price
NOC	No Objection Certificate
OTC	Over the Counter
PPA	Power Purchasing Agreement
PTC	Power Trading Corporation

PX	Power Exchange
PXIL	Power Exchange of India
REC	Renewable Energy Certificate
RLDC	Regional Load Dispatch Centre
RPO	Renewable Purchase Obligations
SEB	State Electricity Board
SERC	State Electricity Regulatory Commission
SLDC	State Load Dispatch Centre
UI	Unscheduled Interchange
WRLDC	Western Regional Load Dispatch Centre

CHAPTER 1. INTRODUCTION

1.1 Background

Today, electricity has become an essential part of modern society. The Quality of a life and economic progress is linked to the electricity consumption. Rapid industrialisation, economic advancement, growing population, and improvement in living standards in many parts of the world have led to the increase in global electricity demand. India is one of such country with the third-largest economy in the world and over one-sixth of the world's population. Peak electricity demand in India is around 153 GW with 3.2% power deficit [1]. Power generation capacity is increasing at a faster rate, but electricity sector faces large transmission and distribution losses, power shortages and poor financial conditions of the distribution companies. Policy makers are forced to contemplate on these issues to keep pace with the growing demand. Power sector reforms were introduced in the India at the critical period of high financial losses and subsidy burden. These reforms have been introduced in phases, and many bold regulatory aspects have changed Indian electricity scenario. Implementation of such reforms has been a major impetus in the significant progress of Indian power sector over the years.

The government of India initiated the restructuring of the power system in 1991 with an objective of achieving technical and commercial potential of the power sector. State Electricity Boards (SEBs) had vertically integrated operational structure which was unbundled into three functional lines i.e. generation, transmission and distribution [2]. Private investors were attracted by easing legal framework and ensuring investment returns to start their own generation units as Independent Power Producers (IPPs) or operate as the licensee in distribution sector [3]. Distribution tariffs were rationalised, and transparency was introduced through complaint handling systems for utilities. The Accelerated Power Development and Reform Programme (APDRP) was introduced to reduce Aggregate Technical and Commercial Loss (AT&C) losses in the power sector and for improving quality and reliability of the distribution sector. State Electricity Regulatory Commission (SERC) and Central Electricity Regulatory Commission (CERC) were set up under regulatory reforms. Electricity Act 2003 [4] is considered as a major step taken toward power sector reforms in India. It introduced open access, power trading, multiple licensing of the distribution system and de-licensing of thermal and captive generation as significant reforms. Initial reforms were focussed at bringing regulatory reforms to attract private investors and unbundling of SEBs. But enactment of Electricity

Act 2003 made development of the competitive bulk power market possible by ending the monopoly in the bulk as well as the retail supply of electricity [3].

The government of India has also introduced renewable promotional policies to develop renewable energy sector as an alternative solution to meet energy needs and energy access in clean and efficient manner. India has an estimated renewable energy potential of 900 MW from commercially exploitable sources *i.e.* wind, solar, small hydro, biomass [5]. Electricity Act 2003 has made it compulsory to the distribution utilities to purchase fixed percentage of power from renewable energy sources. This fixed percentage of power is termed as Renewable Purchase Obligation (RPO). SERCs and CERC have been made responsible for the promotion of generation from the renewable energy sources and cogeneration. National Electricity Policy 2005 was introduced under the provisions of Electricity Act 2003 with an objective of providing electricity access to all and overcome demand deficit. It also had provision for increasing the share of electricity from the renewable energy sources in the total energy mix. Jawaharlal Nehru National Solar Mission (JNNSM) is the ambitious initiative by the government to promote solar energy and aims at the deployment of 100 GW of solar power by the end of 2022. There are financial incentives like Feed-in Tariff (FiT), Generation Based Incentives (GBI) and Accelerated Depreciation (AD) for the promotion of renewable energy.

Power trading recognized as distinctly licensed activity, is also one of the features of Electricity Act 2003 which has increased the competition among the electricity buyers. Before the power sector reforms, SEBs used to procure the power through state-owned plants, from allocated quota through centrally owned plants and from an inter-state exchange of electricity. Long-term Power Purchase Agreements (PPAs) attracted the private investors but could not encourage the competition. Power Trading Corporation (PTC) was set up in 1999 to develop a power market in India. It was set up to promote power trading, develop power market and assist private sector companies to develop a power project. Setting up of power exchanges has helped in multiple entries of buyers and has increased the competition. There is a growth of short-term electricity market where trading occurs through power exchanges, UI mechanism and through short-term bilateral contracts. UI mechanism is a part of Availability Based Tariff (ABT) where charges are levied on the electricity sellers or buyers from deviating from their scheduled injection and withdrawal respectively. The share of short trading in total annual electricity procurement in the Indian power market is continuously increasing from 8% in 2008-09 to 11% in 2013-14 [6]. This reflects the changing market structure and growing competition.

Open access has been provided to the transmission network. Large power consumers or bulk consumers can participate in the power trading by securing the transmission rights. These consumers have power requirements above 1 MW. These consumers participating in short-term trading market have to face the risk of fluctuating price of Day Ahead Market (DAM) in power exchanges and also the risk of paying the penalty in case of over withdrawal under UI mechanism.

1.2 Electricity Act 2003

Electricity Act 2003 has provided thrust to the Indian power sector reforms. It replaced the legislations which were existing in the power sector at that time; Indian Electricity Act 1900, Indian Electricity act 1948 and Electricity Regulatory Commission Act, 1998. This act was brought up to harmonize and rationalize these existing legislations with an objective of creating a competitive power market for quality and reliability of the power supply. Rural electrification was also one of the goals. Setting up of generation facility was made license free, license free distribution for distribution, development of the power trading market was conceived, etc, were some of the features. Modifications were made in the year 2007. Main provisions of the act are as follows.

1.2.1 Open Access

The transmission lines and distribution system can be non-discriminately accessed by any generator or a bulk consumer under the specified regulations. In the case of inter-state open access, CERC regulations are to be followed and in the case of intra-state open access, SERC regulations are to be followed.

1.2.2 Power Trading

Power trading is the trading of the electricity as a commodity with multiple options available deciding its price as well as quantum. In this act, power trading has been recognized as distinct licensed activity regulated by the regulatory commissions.

1.2.3 Regulatory role of government

The government of India was given responsibility to formulate National Electricity Policy, Tariff Act and policy for rural areas and bulk purchase of power. Central

Electricity Authority (CEA) should act as technical advisor to regulatory commissions along with the government.

1.2.4 Consumer Protection

Redresses forum for fast redressal of consumer grievances should be created by distribution utility. Multi-year tariff regime will give an idea to consumers about future electricity tariffs. Consumer tariff should be focussed more on the actual cost of supply instead of cross-subsidies.

1.3 Short-Term Electricity Market

In a wholesale electricity market, power can be traded through spot contracts, forward and future contracts and bilateral contracts. In forward and future markets, for a certain price of purchase and date of delivery, a specified quantity of electricity can be purchased [7]. In future contracts, electricity delivery date can vary and forward contracts expire after a certain time. In India, electricity trading can be done through power exchanges where spot contracts and forward contracts can be traded, or direct transactions can take place through bilateral contracts. These bilateral contracts can be for a long term, medium term or a short term. Short term means for periods less than a year. Long-term Power Purchase Agreements (PPAs) are the long-term contracts between seller and buyer of electricity covering elements like the length of the agreement, commissioning process and curtailment issues. These contracts length may vary between 7 years to 20 years. Medium term contracts have the length between 1 year and 7 years.

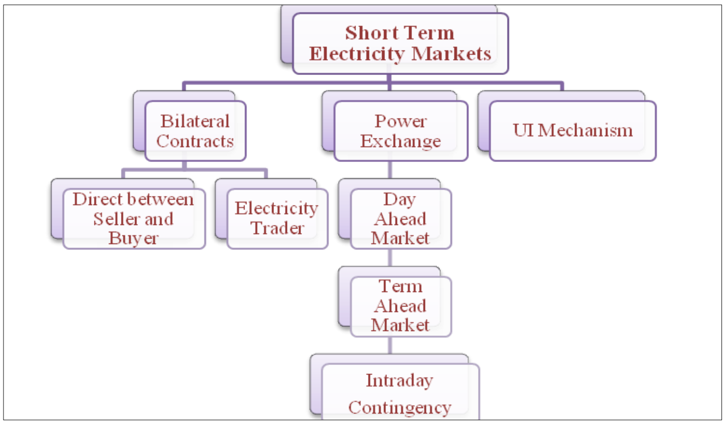

Figure 1.1Snapshot of Short-Term Electricity Market

Short-term bilateral contracts are mostly the inter-state and inter-regional contracts traded either directly or through CERC approved licensee like Inter-State Trading Licensee (ISTL). Short-term electricity market consists of power transactions through power exchanges, short-term bilateral contracts and UI or Deviation Settlement Mechanism (DSM) [6] as shown in Figure 1.1.

1.3.1 Power Exchanges

Electricity Act 2003 introduced power trading and competitive bidding for power procurement in Indian power sector. Power Market Regulations, 2010 [8] provided guidelines for setting up and operation of power exchanges. These regulations were applicable for both OTC (Over the Counter) markets and exchange markets. OTC contracts are the inter-State contracts where electricity trading is done through an electricity trader. On the other hand, Power Exchange market is a market where trading is done with standardised contracts and scheduling is done by load dispatch centres while power exchange acts as the counterparty to these contracts. CERC has permitted trading through PXs with effective from 2008. India has two PX: Indian Energy Exchange (IEX) and Power Exchange of India (PXIL). A PX has a structure where fair, and efficiency price discovery is made maintaining anonymity of participants. It functions under the norms of CERC with activities like price discovery mechanism, clearing and settlement procedure, risk management, and default and penalty mechanism [9]. Following are the delivery based contracts transacted in exchanges:

1.3.1.1 Day Ahead Contracts

Day Ahead contracts are the contracts where trading of electricity takes place one day before the delivery of electricity. There is double sided anonymous auction mechanism to determine the price and quantum of electricity to be traded [10]. There is a trading block of 15 minutes allowed. Market Clearing Price (MCP) is determined by the intersection of demand and supply curves. Minimum No Objection Certificate (NOC) of 0.1 MW is required. Pool based scheduling of the traded power is done by the NLDC.

1.3.1.2 Term Ahead Contracts

Term Ahead Contracts include Intra-Day, Day Ahead Contingency, daily and weekly contracts [10]. Intra-day and contingency contracts include trading of electricity after the closure of day-ahead markets and delivery of electricity takes place on the same day or the next day. In daily contracts, delivery of electricity take place after 4th day from the day of transactions to the next seven days. In all these contracts, continuous type of trading takes place which is different from closed auction. In auction system, price matching is done after receiving all bids and offers. But in continuous trading, continuous matching takes place based on price and time. Weekly contracts are based on open auction system where trading is done for the delivery of electricity for the next week.

1.3.2 Deviation Settlement Mechanism (DSM)

Electricity transacted under Deviation Settlement Mechanism (DSM) or Unscheduled Interchange (UI) mechanism is considered as part of short-term transactions. UI mechanism is a part of Availability Based Tariff (ABT) which came in the year 2002 for determining the tariff system for electricity generators. UI mechanism has sole objective of maintaining grid frequency in the narrow band as per Indian Electricity Grid Code (IEGC). Present band is 49.7 Hz to 50.05 Hz. In this mechanism, a seller has to pay penalty for under-injection of electricity than the scheduled injection and a buyer has to pay penalty for over-withdrawal of electricity than the scheduled withdrawal. Thus a seller of buyer has to pay penalty for causing imbalance in the power grid at the real time. These deviations from the scheduled injection or withdrawal are determined through special metering in 15 minute time block. The scheduling of injection and withdrawal is done through load dispatch centres. State Load Dispatch Centres (SLDCs) manage the transmission system in their respective grids while Regional Load Dispatch Centres (RLDCs) manage and operate regional grids. RLDCs prepare the dispatch and withdrawal schedule for the sellers and buyers considering availability, network constraints and securities. CERC specifies the penalty rates according to grid frequency. According to Deviation Settlement Mechanism and related matters regulations, 2014, penalties are also imposed on the volume of imbalances [11]. According to it, rates have been mentioned below and UI curve has been plotted in Figure 1.2.

a) For over withdrawal less than the minimum of 12% of scheduled interchange or 150 MW

   Charge for unscheduled deviation for each 0.01 Hz step is 35600 Rs. /MWh for frequency range 50 Hz – 50.05 Hz and 20840 Rs. /MWh for frequency range 50 Hz – 49.7 Hz.

b) For over withdrawal more than minimum of 12 % of scheduled interchange or 150 MW

If over withdrawal is between 12 % - 15 % of scheduled interchange or 150 MW to 200 MW, then additional charges as 20 % of a) are levied. If over withdrawal is between 15 % - 20 % of scheduled interchange or 200 MW to 250 MW, then additional charges as 40 % of a) are levied. If over withdrawal is more than 20 % of scheduled interchange or more than 250 MW, then additional charges as 100 % of a) are levied.

c) If under withdrawal is more than 12 % of scheduled interchange or 150 MW, then UI charge is zero to discourage consumers from using UI as an earning tool.

d) At 50.05 Hz and above UI charge is zero.

Considering consumer is over withdrawing within the permissible deviation that is less than the minimum of 12% of scheduled interchange or 150 MW, for frequency above the 49.7 Hz, UI curve is as shown below.

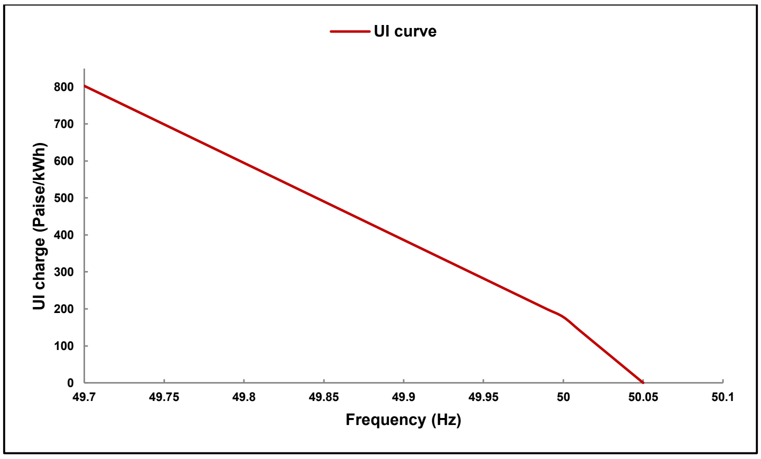

Figure 1.2 UI Curve According to DSM 2014

1.3.3 Short-Term Bilateral Contracts

Short-term bilateral contracts are signed between the two parties where one is a seller and other is a buyer of the electricity for a specified short period. The terms are negotiated and conditions are mutually agreed by both the parties.

1.4 Renewable Purchase Obligations (RPO)

Electricity Act 2003 has provision for the promotion of generation from renewable energy sources to counter environment deterioration and non-uniform resource distribution. Obligated electricity consumers are required to purchase fixed percentage of power from the renewable energy sources in a financial year according to the act. This obligation is called Renewable Purchase Obligations (RPO). State Electricity Regulation Commission (SERC) has the responsibility of ensuring grid connectivity and deciding RPOs. These eligible consumers are distribution licensee, open access consumers, and Captive Power Plant (CPP) owners. SERCs determine the eligible consumers for the respective states. These consumers can fulfil RPO either through Feed in Tariff (FiT) contracts or through Renewable Energy Certificates (RECs).

1.4.1 Feed-in Tariff (FiT) contracts

FiT contracts are the long-term power purchase contracts with a renewable energy generator where tariff to the energy fed into the grid is nearly equal to the cost of production of renewable energy. This preferential tariff is decided by the SERC for the respective states.

1.4.2 Renewable Energy Certificate (REC)

In Indian, some states are rich in renewable energy sources while some are not. For fulfilling the RPO, eligible entities in renewable energy deficit states can purchase the Renewable Energy Certificates (RECs). One REC is equivalent to the 1 MWh of electricity injected into the grid. The cost of electricity generated from the renewable energy source is considered as the sum of the cost of electrical energy and environmental attributes. REC shows environmental attributes of the renewable energy generators. The electrical component of the renewable energy can be sold to the distribution utilities for the price less than the average pool price or to the third party or through PXs. It is a market-based instrument where RECs are traded in PXs on the last Wednesday of every month. CERC has set the limits of the floor (minimum) and forbearance (maximum) price. There are two types of RECs; one is solar RECs, and other is non solar RECs. Renewable energy sources are decided by MNRE. For the financial year 2012-2016, forbearance and floor price for non solar has been 3300 Rs./ MWh and 1500 Rs./MWh respectively. While forbearance and floor price for solar REC has been 13,400 Rs./MWh and 9300 Rs./MWh for the same period. REC trading started since the year 2011. The validity of REC is 730 days from the date of issue.

1.5 Research Objective

Last sections briefly described the short-term electricity market and renewable promotional policies in India. Planning of electricity procurement in a short-term electricity market for an open access consumer is necessary due to multiple options available under uncertain price and grid conditions with obligations for renewable energy purchase. Literature shows that a very few study has been done in Indian power market with the consumers' perspective. To the authors' knowledge, mean-variance risk approach has not been used in any research to minimize the cost of electricity purchase for a large Indian electricity consumer.

Thus, present work focuses on:

- Development of short-term electricity planning model for an open access consumer in India.
- Inclusion of uncertainty due to grid imbalances and market price.
- Inclusion of flexibility in the demand of the consumer.
- Inclusion of renewable promotional policies in the model.
- Impact of planning model on the grid frequency.

1.6 Organization of Thesis

This thesis has been divided into six chapters. A brief outline of each chapter is given below:

Chapter-1. Introduction

Chapter-1 gives a brief background of prevalent policies and regulations in the Indian power sector related to power trading, grid discipline, renewable energy promotion and large electricity consumers. An outline of the research objectives is also given, and the chapter ends with a brief description of the research procedure followed in this work.

Chapter-2. Literature Review

Chapter-2 gives a summary of the research work done till now in the related areas. The literature review has been divided into four major topics – a) Large Electricity Consumers b) Short Term Power Trading c) UI Mechanism d) RPO. The research objective is identified, and scope of the present work is presented.

Chapter-3. Methodology

Chapter-3 gives the brief overview of the stepwise process undertaken for achieving the research objective. It includes a brief description of GAMS and the solvers used for solving the mathematical model for finding the optimized results.

Chapter-4. Problem Formulation

Chapter-4 gives details of problem formulation for the identified objective for two different cases. The mathematical model has been presented explaining the optimization approach taken for handling the risk for the mixed integer non-linear objective function.

Chapter-5. Case Study and Results

Chapter-5 gives the case study related data and the results obtained after running the GAMS model successfully. The results are discussed with important findings.

Chapter-6. Conclusions and Future Scope

Chapter-6 gives the important conclusions derived from the results and the future improvement which can be done for the thesis work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Major Indian power sector reforms, short-term electricity market, and related policies and regulations were explained in the last chapter. Research objective has many elements which have been individually identified and researched with different perspectives in the literature. This chapter has the focus on the researches done on these elements, their significance, and their contribution. The relevance of the research objective can be easily understood by the end of the chapter.

Development of electricity market is based on the fact that electricity is considered as a commodity with inverse demand and supply relationship. Technical literature with the perspective of the generators is abundant in the electricity market, but researches with the perspective of the consumers in the electricity market have recently gained the pace. With different electricity market structures in different countries and beginning of the era of deregulation and competitive market, a variety of mathematical models and solution techniques have been presented [12].

The literature survey is organized in line with similarity to the work done in this thesis. In this literature review emphasis is directed on:

- Large Electricity Consumers
- Short-Term Power Trading
- UI Mechanism
- RPO

2.2 Large Electricity Consumers

Large electricity consumers are the consumers connected to high voltage grid. Researches done for retailers have been neglected in this section as the thesis work is focussed on the large electricity consumers. Retailers differ from the consumers in the respect that retailers buy energy for consumption of its consumers but large consumers buy energy for the self-consumption. Researches on large consumers generally have four approaches; definition of objective, proposal of methodology, consideration of risk and sensitivity analysis. In this section, papers related to large electricity consumers in the wholesale electricity market have been discussed.

Kirschen (2003) presented the tools for the participation of retailers and consumers in the electricity market. This paper focussed on the perspective of demand side in the electricity market and a short discussion was also presented on the effect of short-run demand elasticity on the market operation. These tools are price forecasting, production optimization, and selection of best contract. It explained price forecasting for spot market prices is essential for the trading decisions while it is also complex due to the involvement of both load and generation side. It discussed the storage and consumption strategy of the consumers if the use of quality storage does not affect other production costs. It showed with an example how optimal production strategy can be developed for higher returns. And lastly, consumers can also take advantage of other types of contracts available in the market and select the best type according to their needs [13].

Conejo et al. (2005) addressed the problem of self-generating large consumers procuring form pool and bilateral transactions without considering uncertainties. The mathematical formulation is of mixed integer linear programming model. A penalty cost system was included for over consumption and under consumption of electricity from the bilateral contracts. For determining self-generation cost, a piecewise linear convex approximation was used and also selling facility of self-generated energy to the pool was included in the model. It was assumed that all data is available. The objective function was cost minimization. Results showed that the there is important percentages of bilateral contracts, pool contract and self-generation in the optimal purchase signifying that the consumer does not solely rely on a specific type of contract. Also purchasing from the bilateral contracts and self-generation helped in significant reduction of the cost of purchasing for the consumer [14].

Conejo and Carrion (2006) solved the optimal purchase problem as in [14] with mean-variance tool. Based on Markowitz theorem, risk constrained cost minimization objective function was formed. Uncertainty is considered in the pool prices, and forecasted price and historical price are considered for the formation of the covariance matrix. The demand of the consumer is considered as deterministic. Mathematical formulation is a mixed integer non-linear type model. Results showed the risk versus cost trade-off faced by the consumer where higher risk represents a low investment. Results showed that the higher cost volatility has led to the lesser cost of procurement [15].

Carrion et al. (2007) addressed the problem of electricity procurement by the large consumers with stochastic programming approach. Problem type is multistage stochastic integer programming problem. Conditional value-at-risk (CVaR) method is used for limitation of risk arising due to the uncertainty of pool price. Scenario reduction technique based on the Kantorovich distance was used to trace the optimization problem [16].

Zare et al. (2010) addressed the price uncertainty of the pool price for the large consumer using the Information Gape Decision Theory (IGDT). This tool does not consider the nature of uncertainty. The results showed the aspects of robust bidding strategy derived for the large consumers participating in a day ahead market [17].

2.3 Short Term Power Trading

This section discusses the literature overview of the short-term electricity market. Short-term power market in India is in its nascent stage. Many type of research have been the review of the policies and regulations related to the development of short-term electricity market in India. While some authors have given very good suggestions for the future development, the following literature is providing the details of short- term electricity market, its implementation, and its importance.

Khaparde (2004) presented the snapshot of the Indian electricity market including features of restructuring and the regulations. It discussed the features of the system operation in the deregulating Indian electricity market scenario. Main features of Electricity Act 2003 were presented and it was discussed that how these features impact the power system restructuring. Open access to the transmission and distribution was discussed and proposed transmission tariff system was discussed [18].

Singh (2006) elaborated the power sector reforms in Indian electricity market and welcomed them with the discussion on their potential impact on the future energy needs. It was discussed that how open access opens the way for multiple licensees which in turn open the way for healthy competition. More attention is required on the distribution system for the long-term growth and other challenges hindering this growth like political coupling, or high distribution losses should also be addressed. It was explained that power sector reforms have a long way to go for fruitful results, and immediate judgement is not guaranteed. Many inputs are required to be fed in between inspired by the researches and experiences to recourse the power sector reforms in India [19].

Singh et al. (2010) discussed the status of competition in the power sector after open access and issues related to it. It highlighted the efforts made by different SERCs in their respected states for guiding the competition in the wholesale electricity market. Status of competition and policy and regulations prevailing in all sectors of power system were discussed. Challenges for the completion in the electricity market like transmission system pricing, efficient market pricing, and tariff designs for demand response have been explained [20].

Shukla and Thampy (2011) further analysed the wholesale electricity market and suggested measures for increasing the competition in the market. It reviewed the electricity trading mechanisms prevailing in the India. It included long-term electricity PPAs and short-term contracts like short-term bilateral contracts, UI mechanisms, and PXs. After analyzing the competition with different management tools, measures were suggested to improve the competition in the wholesale electricity market [21].

2.4 Unscheduled Interchange (UI) Mechanism

UI mechanism has been explained in the last chapter. This section will analyze the implementation of UI mechanism in the Indian electricity market. Following literature discuss its advent and then journey towards becoming a powerful and dynamic measure.

Bhushan (2005) explained Availability Based Tariff (ABT) in the Indian power market. The three part systems of the ABT were explained and its working mechanism considering roles of generating stations, state distribution companies, dispatch centres, etc. UI mechanism which is part of ABT and in itself is a novel approach for maintaining grid discipline by the India was elaborated. The system of paying a penalty when deviating from the schedule was discussed with the help of curves. The relation between UI rate and system marginal cost was examined and its impact on the optimizing the system operation was explained [22].

Soonee et al. (2006) argued that UI mechanism which is part of ABT can be moreover considered as a real-time balancing mechanism in India. It discussed both pre-ABT scenario and post-ABT scenario. Post-ABT, frequency band has succeeded in narrowing down. This mechanism was compared to the AGC (Automated Generation Control) system which helps in maintaining frequency in the generating stations to the nominal value. It was suggested that the open access and UI mechanism will help greater in the demand response [23].

Gupta et al. (2008) presented an artificial neural network based model to predict the frequency in the post-ABT Indian grid conditions. Due to complex non-linear relationships in the data for the short term, this technique was used to predict the grid frequency. The results were analyzed for a generating gas station for declaring optimal scheduled injections in the grid on a day-ahead basis [24].

Vaitheeswaran and Balasubramanian (2010) developed a mid-term planning model for a generating station operating under ABT regime in India. Risk constrained profit maximisation technique using stochastic programming was implemented. Daily decisions for the availability of the generating station have been made after deciding an optimum annual availability target. A set of scenarios has been developed for modelling uncertainty in the UI rate, load, and generation availability. CVaR risk measure was used for considering risk arising due to UI. The General Algebraic Modelling System (GAMS) CPLEX system was used for solving this stochastic linear programming. The results showed that the impact of fuel nature is more on the decision strategy of the generating station [25].

Panda (2014) presented the model for a generator participating in the day-ahead electricity market under ABT in India. Risk constrained profit maximization has been done with CVaR risk tool. In the research, authors found the optimal value of UI charge for the maximum profit earnings. Efficient frontier has been obtained to see the effects of risk for the expected profit making of the generator. With the increasing value of the risk, the value of expected profit decreases. The impact of UI rate on the availability of the generator has been analysed [26].

2.5 RPO Mechanism

Literature for RPO mechanism consists of both its review and its mathematical representation as explained below.

Goyal and Jha (2009) discussed the RPO mechanism in details while suggesting a framework for future growth of renewable energy in the country. They also discussed the RECs and its role in achieving RPO for SERCs. Major features of the policies which are playing the key role in renewable energy growth in the country were once again revised and the role which SERCs have played in their states for compliance of RPO was presented. As the role of SERCs grows bigger, they should carefully plan the achievable RPOs and surcharges. RECs were suggested in detail with their importance to the states where renewable energy generation is negligible [27].

Soonee et al. (2012) discussed the various aspects associated with REC mechanism after it implementation in the year 2011. Salient features related to the REC mechanism were discussed and four stage processes of REC and its trading at the power exchanges was explained. Issues and future challenges were also discussed, like issues of small generators, cyber security and RPO monitoring at the state level [28].

Veena and Abhyankar (2012) proposed a model for RPO fulfilment by load serving entities while minimizing the risk due to wind power generation and volatile REC price. Fuzzy approach has been used to model the risk. The problem type is a multi-objective type with cost and risk minimisation objective. The load-serving entity can take the decision regarding purchasing of RECs from the market beforehand [29].

Shereef and Khaparde (2013) analysed in detail the REC trading in Indian electricity market and other renewable energy promotional policies. RPO for different states as set by SERCs and RPO proposed as per state's renewable energy status were compared. Trading of RECs at power exchanges has been examined. The authors concluded that the RECs are unsold in the market with market price hitting the floor price. To improve the health of REC market, it is necessary for the state agencies to penalize the defaulters and make stricter rules. Many new suggestions were presented for RPO compliance like changing frequency of RPO compliance and providing financial incentives to the already debt-ridden discoms [30].

2.6 Conclusion from Literature Review

Electricity procurement planning for a large Indian consumer is still the untouched research area as not much work has been done on this. Based on literature review the following conclusions can be drawn:

- A number of consumer electricity planning strategy has been devised in countries other than India to minimize the risk and cost of purchasing. Many risks measuring tools have been used in these models like mean-variance approach, CVaR or stochastic approach.
- In Indian electricity markets, planning model for the generators under the restructured power system have been proposed which deals with UI, RPO and day-ahead market. These models deal with the objective of maximising the profit and minimising the risk due to the uncertain price or frequency rates. But such type of planning models for the consumers is rare.

- Many types of the research have discussed the impacts of new regulatory reforms in Indian power market and have analyzed their performances and have also given suggestions for the improvement. These researches are review based and lack the mathematical representation for better understanding.
- Many researches use the frequency linked mechanism to find the UI rates in the system. As the UI rates are being calculated at the real time, the inclusion of impact of UI mechanism in the planning model should be analyzed beforehand.

2.7 Scope of Present Work

As it is obvious from the above researches that the regulatory reforms are important in the Indian power market and their correct implementation can not only enhance a healthy competition in the wholesale electricity market but can also promote renewable energy sources, benefit all the participants whether generators or the consumers and bring efficiency in the system. So the study of the impact of these regulations and inclusion of them in planning model is very important for the optimisation of resources. Given of the above findings, following scope of the present work have been identified:

- To develop a planning model for a large consumer participating in the wholesale electricity market post the power restructuring reforms.
- To study the effect of UI mechanism on the planning model.
- To include renewable energy promotional policies in the planning model.

CHAPTER 3. METHODOLOGY

3.1 Introduction

After finding research objective in the last chapter, the major task remains of fulfilling that objective. This chapter deals with the brief outline of the steps being used for the thesis work. Figure 3.1 gives the different stages of the development of the research work.

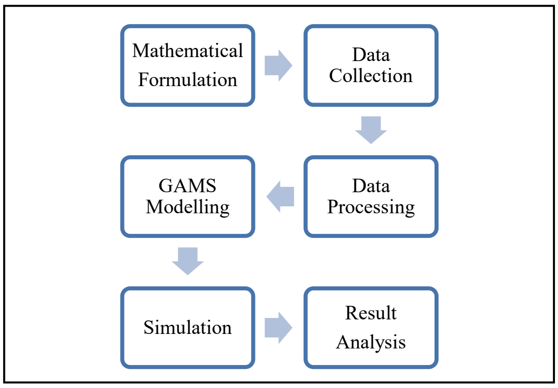

Figure 3.1 Process Flow for Research Work

These steps have been explained in detail in the following sections.

3.2 Mathematical Formulation

The research goal is transformed into a problem statement. This problem statement is mathematically formulated with unknown variables and known parameters. This mathematical formulation is an optimization problem with an objective and constraints. This whole part has been discussed in the next chapter.

3.3 Data Collection

Known parameters in the mathematical formulation are given values from the case study conducted. The case study involves the practical scenario resembling the problem statement. Data for known values is collected from different sources. As explained in Chapter 5, there are two cases in the thesis work which different perspective according to their problem statements. Data collection has been done judiciously taking care of policy issues, reciprocity, and interpretation. Some data has been assumed with generalised behaviour in the further studies.

3.4 Data Processing

Data collected need to be segregated and to be processed such that it can be given as input values in the optimization software. As past information is being used for finding the nature of some input values, a detailed processing in the format required by the mathematical model has been done. These data have been presented along with their case studies in the Chapter 5 mostly in tabular or pictorial views.

3.5 GAMS Modelling

The General Algebraic Modelling System (GAMS) has been used for solving the mathematical model as described in the Chapter 4. It is a high-level modelling system which can be used to solve complex linear, non-linear, mixed integer type optimization problem. It has language compiler and integrated solvers for solving the optimization problems [31]. Features of GAMS system are listed below.

- Users' models are unaffected by the change in algorithm methods.
- There is a separation of logic and the data which helps in reducing the complexity of the model.
- Data representation is very elemental and concise. Data can be entered in its basic form without requiring any special structure.
- GAMS model is portable and can be easily transferred to another system with just one document of its model.

Although many software is available for solving the optimization problems like MATLAB, Python, etc, GAMS is user-friendly, easy to learn, helps in solving large-scale problems and can handle mixed integer problems smoothly. GAMS specifications and solvers have been discussed in the following paragraphs:

3.5.1 GAMS Specifications

GAMS system used for modelling and solving the optimization problem has the following specifications.

Table 3.1 GAMS Specification

	Specification
Build	23.8.2 WEX 32359.32372 WEI *86_64
GAMSIDE build	32351/32372
Module	GAMS Base Module

GAMS version 23.8 contains major changes in the system as compared to previous versions like the handling of stochastic programming in GAMS.

3.6 Simulations

There are different model types and solvers available in GAMS. These solvers are not developed by GAMS but are linked as third-party solvers. For solving the mixed integer non-linear type problem as the thesis problem type explained in the Chapter 4, solvers used are SBB- CONOPT [32].

3.6.1 CONOPT

CONOPT is the solver used for the large scale non-linear optimization problems. It is based on the Generalised Reduced Gradient (GRG) method. GRG is an active set method in which inequality constraints are changed into linear constraints using the linear slack variable. Variables are divided into basic and non basic variables and constraints are removed by replacing basic variables by non-basic, variables. This process repeats till the optimal solution is found. This type of process is successful for solving the difficult models with reliability and speed.

3.6.2 SBB

It is a new solver introduced in the later versions which has been successful in solving the mixed integer non-linear programming problems. It works better with the models with few variables but difficult non-linearity constraints and non-convexity. If non convex problems are solved using non linear programming solvers only, then the problem may arise due to a failure of solvers or a locally feasible node can be declared as infeasible. It combines the branch and bound method with a standard non-linear problem solvers like CONOPT. It bounds the nodes to get expanded. It selects the nodes to be expanded and also when, and other criterion tells if the optimal solution has been found.

CHAPTER 4. PROBLEM FORMULATION

4.1 Problem Statement

With the background of deregulated power industry and major power reforms, a large electricity consumer in India has better options of power purchase to meet its electricity demand. It can reduce its power purchasing cost but also faces the uncertainty of price and frequency. This changed electricity market scenario with the perspective of the large consumer has been presented in this chapter with the different cases and has been mathematically formulated.

A large electricity consumer is participating in the short-term electricity market. It has many options to purchase the power. It has an option of bilateral contract with a predefined price of purchase. It can also purchase power through power exchanges in the day-ahead market. It also has a self-generation unit. It also needs to satisfy the RPO by purchasing power through FiT contracts or RECs. There is an uncertainty of price in day-ahead market. Due to uncertainty of grid frequency, the consumer may end up paying a penalty for over withdrawal of power under DSM. Two cases have been presented in the following sections. In the first case, consumer minimizes its purchase cost in its planning model by shifting its demand. In the second case, flexible load modelling has also been added.

This work focuses on the problem of an open access consumer in India, willing to plan an optimal short-term power procurement strategy for a future period, under the uncertainties of UI charges and DAM prices from available options. This consumer is considered as an obligated entity to fulfil RPO. The consumer balances its flexible demand from UI to have the minimum penalty. The overall problem is of cost minimization while uncertainties have been addressed with variance.

4.2 Optimization Tool

Mean-Variance Optimization technique has been used for mathematically modelling the problem. Mean-variance portfolio theory originated from the Markowitz portfolio theory [33] describes how investments can be optimally allocated among different portfolios (assets) considering trade-off between risk and return. If no uncertainty is considered then, portfolio giving the maximum returns (profits) can be selected. But when uncertainty comes in the picture, then investment can be allocated to different assets such that risk is diversified. Expected return and risk are calculated from the mean-variance tool from the past information. Expected return is determined from the weighted average expected return on the assets. Variance is used as a risk measure such that it gives the variability of expected returns. Larger variance denotes the higher risk. If two or more than two risky assets are present, then the correlation of variability between these assets is also calculated in the risk given by covariance. Efficient frontier is a portfolio representing values of maximum returns at any value of risk. In the mathematical model presented in the next section, expected return (cost) is minimized using variance as risk measuring tool.

4.3 Mathematical Formulation

Two cases have been examined in this work. The first case deals with the uncertainty of both DAM price and UI rate while in the second case UI rate has been calculated from a practical Indian grid condition. These two cases have been identified for understanding the short-term electricity model and creating all possible scenarios for the consumer to manage resources while handling uncertainty. In the first case, consumer shifts its demand while in the second case; added feature of flexible loads helps the consumer in better planning of demand shift. The second case is a different yet improved way of showing possible efforts that can be made by a large consumer in demand response in Indian power system.

4.3.1 Case 1

An open access consumer is purchasing power from different options available as mentioned in the following part. It has some percentage of flexibility present in its demand which it can shift. The uncertainty of spot market price and UI rate has been considered using mean-variance approach.

A. Power Procurement from Bilateral Contracts

Total cost of buying from bilateral contracts for the time period T is given by C^b,

$$C^b = \sum_{t=1}^{T} \lambda_t^b P_t^b \qquad (1)$$

$$P^{b,\min} v_t \le P_t^b \le P^{b,\max} v_t \qquad (2)$$

P_t^b is power purchased from bilateral contract at time t. $P^{b,\min}$ and $P^{b,\max}$ are the minimum and maximum power purchase limits in the bilateral contract respectively. v_t is the binary variable which is one if power is purchased from the contract otherwise it is zero.

B. Power Procurement from Spot Market

Power purchased from spot market (DAM) is P_t^d. It is assumed that pool prices follow normal distribution function with average of $\lambda_t^{d\exp}$ and variance of $\lambda_t^{d\,\mathrm{var}}$, $\forall t$, total cost of purchasing from spot market for time period T is given by C^d,

$$C^d = \sum_{t=1}^{T} \lambda_t^{d\exp} P_t^d \tag{3}$$

$$P_t^d \geq 0 \tag{4}$$

C. Power Procurement from FiT Contract

Total cost of purchasing from FiT contract for time period T is given by C^f,

$$C^f = \sum_{t=1}^{T} FiT\, P_t^f \tag{5}$$

$$0 \leq P_t^f \leq P^{f,\max} \tag{6}$$

Where FiT is the price of the contract which is assumed constant throughout the planning horizon T. P_t^f is power purchased from FiT contract at time t with $P_t^{f,\max}$ as the maximum power purchase limit in FiT contract.

D. REC purchase

Here only non solar RECs purchase is considered. Solar RECs are purchased for fulfilling solar RPO and non solar RECs are purchased for fulfilling non solar RPO. To reduce ambiguity, only non solar RECs purchase has been envisaged in the work. Cost of purchasing from non solar RECs is given by C^{REC},

$$C^{REC} = \sum_{t=1}^{T} \lambda^{r\exp} REC \tag{7}$$

$$0 \le REC \le n \tag{8}$$

Where REC is the number of RECs purchased. n denotes the maximum number of RECs that can be purchased. $\lambda^{r\exp}$ is the expected non solar REC price. For short term planning like one month, this can be considered deterministic.

E. Self-Generation Cost

Assuming a self-generation unit installed onsite, generation cost in time T is given by C^g,

$$C^g = \sum_{t=1}^{T} c_t^s + c\, u_t + b\, P_t^g + a\, (P_t^g)^2 \tag{9}$$

c is the no load coefficient, b is the linear coefficient and a is the quadratic coefficient. P_t^g is the self generated power at time t. Start up cost at time t if unit is started at time t is given by c_t^{su},

$$c_t^{su} \ge c^{su} (u_t - u_{t-1}) \tag{10}$$

Where c^{su} is the constant start up cost. u_t one if unit is on and otherwise it is zero. Operating constraints of generation unit is given as:

$$P^{g,\min} u_t \le P_t^g \le P^{g,\max} u_t \tag{11}$$

$P^{g,\min}$ and $P^{g,\max}$ are the minimum and maximum generation limits respectively. And ramping constraints with R^{up} and R^{dn} as ramp up and ramp down limits respectively are given as:

$$P_t^g - P_{t-1}^g \le R^{up} u_t \tag{12}$$

$$P_{t-1}^g - P_t^g \le R^{dn} u_{t-1} \tag{13}$$

F. UI charge

UI charge is calculated from the product of UI rate and deviation caused in a 15 minute block time. Here hourly trading has been considered. So UI rate is taken as average of four 15 minute UI rates in an hour. Total UI charge for time period T is given by C^{ui}

$$C^{ui} = \sum_{t=1}^{T} \lambda_t^{u\exp} UI_t \qquad (14)$$

UI_t is the deviation from the scheduled power at time t which is a free variable. $\lambda_t^{u\exp}$ is the expected UI rate calculated from historical information for an hourly trading interval. Constraints on the UI_t can be expressed based on the deviation settlement mechanism as

$$-\delta * SI_t \le UI_t \le \delta * SI_t \qquad (15)$$

Where SI_t is the actual demand and δ is the percentage of deviation caused if SI_t has been scheduled.

4.3.1.1 Objective function

The total cost of power procurement from available above options and UI charge can be written as $C^{\exp}$,

$$C^{\exp} = C^d + C^b + C^g + C^f + C^{REC} + C^{ui} \qquad (16)$$

Risk arising due to uncertainty of UI rate and spot market price can be written as C^{risk}

$$C^{risk} = \sum_{t=1}^{T} \lambda_t^{u\,\mathrm{var}} (UI_t)^2 + \sum_{t=1}^{T} \lambda_t^{d\,\mathrm{var}} (P_t^d)^2 + 2 \sum_{t=1}^{T} \lambda_t^{\mathrm{cov}} UI_t P_t^d \qquad (17)$$

$\lambda_t^{u\,\mathrm{var}}$ is the variance of UI rate. λ_t^{cov} is the covariance of UI rate and spot market price.

Objective function can be written as:

$$\textbf{Minimize}_{\,P_t^d, P_t^b, P_t^g, P_t^f, UI_t, u_t, v_t, c_t^s \quad \forall t; REC} \quad C^{\exp} + \alpha C^{risk} \qquad (18)$$

Where α is a risk weighing factor. This objective function needs to be minimized subject to the constraints given below.

4.3.1.2 Constraints

a) Demand Balance

Demand constraint for the consumer at time t can be modelled as:

$$SI_t + UI_t = P_t^g + P_t^b + P_t^d + P_t^f \tag{19}$$

SI_t is deterministic in nature. If P_T is total power procurement for time period T, then UI term is included in the constraint as

$$\sum_{t=1}^{T} SI_t + \sum_{t=1}^{T} UI_t = P^T \tag{20}$$

The flexible consumer can also reduce its demand up to certain extent i.e. $P^{T,\min}$

$$P^{T,\min} \leq P^T \tag{21}$$

b) RPO constraints

RPO can be achieved either through FiT contracts or RECs purchase. No distinction has been made on RPO based on solar and non-solar power generation.

$$REC + \sum_{t=1}^{T} P_t^f \geq RPO\ P^T \tag{22}$$

$$REC \leq RPO\, P^T \tag{23}$$

Where RPO is the quantum of power to be purchased under RPO target for the consumer for the planning period T.

c) Minimum or Maximum purchase constraints

These constraints for different type of options are given in the equations (2), (4), (6), and (8).

d) UI Constraint

Constraint on UI is given in the equation (15).

e) Self Generation Constraints

These are given in the equations (10)-(13).

4.3.2 Case 2

This case envisages the short-term planning model for the consumer procuring from the bilateral markets, spot markets, and self-generation considering the uncertainty of spot market price. UI mechanism is integrated into the planning model impacting the scheduled demand and the grid frequency. In this case, the Consumer has flexible loads which can be modelled. The consumer is now participating in two spot markets. UI rate is calculated from UI curve instead of historical information. The uncertainty of spot market prices has been handled using mean-variance approach.

A. Power Procurement from Bilateral Contracts

Total cost of buying from bilateral contracts for the time period T is given by C^b,

$$C^b = \sum_{t=1}^{T} \lambda_t^b P_t^b \tag{24}$$

$$P^{b,\min} v_t \le P_t^b \le P^{b,\max} v_t \tag{25}$$

P_t^b is power purchased from bilateral contract at time t. $P^{b,\min}$ and $P^{b,\max}$ are the minimum and maximum power purchase limits from the bilateral contract respectively. v_t is the binary variable which is one if power is purchased from the contract otherwise it is zero.

B. Power Procurement from Spot Market

There are two spot markets; one is IEX's DAM and another one is PXIL's DAM. Power purchased from IEX spot market is P_t^{di} and power purchased from PXIL market is P_t^{dp}. It is assumed that pool prices follow normal distribution function with average of $\lambda_t^{di\exp}$ and $\lambda_t^{dp\exp}$ and variance of $\lambda_t^{di\,\mathrm{var}}$ and $\lambda_t^{dp\,\mathrm{var}}$, $\forall t$, total cost of purchasing from spot market for time period T is given by C^d,

$$C^d = \sum_{t=1}^{T} \lambda_t^{di\exp} P_t^{di} + \sum_{t=1}^{T} \lambda_t^{dp\exp} P_t^{dp} \tag{26}$$

$$P_t^{di} \ge 0 \tag{27}$$

$$P_t^{dp} \ge 0 \tag{28}$$

C. Power procurement for RPO

A fixed percentage of demand, m, has been considered to be purchased from RPO. C^{RPO} is the cost of purchasing this power.

$$C^{RPO} = m * P^T * \lambda^f \tag{29}$$

Where P^T is the power procurement for the planning period T and λ^f is the fixed cost of purchasing for RPO which here has been considered equivalent to FiT price.

D. Self-Generation Cost

Assuming a self-generation unit installed onsite, generation cost in time T is given by C^g,

$$C^g = \sum_{t=1}^{T} c_t^s + c\, u_t + b\, P_t^g + a\, (P_t^g)^2 \tag{30}$$

c is the no-load coefficient, b is the linear coefficient and a is the quadratic coefficient. P_t^g is the self-generated power at time t. Start up cost at time t if unit is started at time t is given by c_t^{su}

$$c_t^{su} \ge c^{su}(u_t - u_{t-1}) \tag{31}$$

Where c^{su} is the constant start up cost. u_t one if unit is on and otherwise it is zero. Operating constraints of generation unit is given as

$$P^{g,\min} u_t \le P_t^g \le P^{g,\max} u_t \tag{32}$$

$P^{g,\min}$ and $P^{g,\max}$ are the minimum and maximum generation limits respectively. And ramping constraints with R^{up} and R^{dn} as ramp up and ramp down limits respectively are given as

$$P_t^g - P_{t-1}^g \le R^{up} u_t \tag{33}$$

$$P_{t-1}^g - P_t^g \le R^{dn} u_{t-1} \tag{34}$$

E. UI Charge

UI charge, C^{UI}, is calculated from UI curve. λ_t^u is calculated from the frequency f_t in the UI curve.

$$f_t = 50 - \frac{L_t - [G_t - UI_t]}{FR * L_t} \qquad (35)$$

$$C^{UI} = \sum_{t=1}^{T} \lambda_t^u UI_t \qquad (36)$$

f_t is the frequency at time t. L_t is system demand at time t. G_t is system generation at time t. UI_t is deviation caused by the consumer in the system at time t. FR is the frequency fall ratio.

F. Flexible Load Modelling

Demand for the consumer at time t can be divided into two parts. One is the base demand, P_t^d , which is known and another one is the unknown demand, ΔP_t^d which can be met by a flexible load. The curve for a flexible load is given below [34].

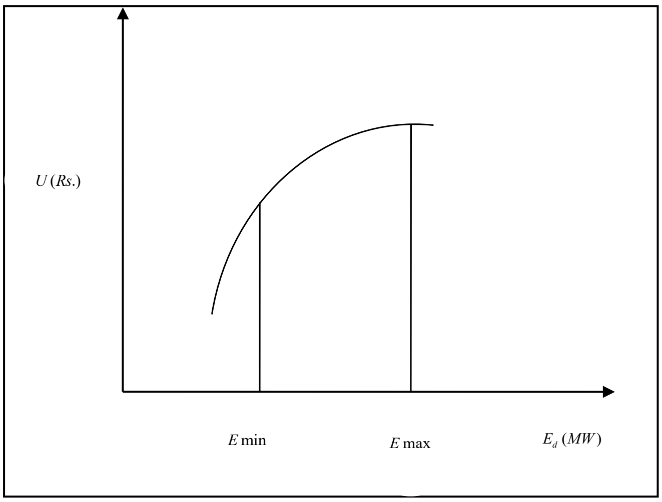

Figure 4.1Benefit Obtained by a Flexible Load

Here E min and E max are the minimum and maximum energy consumption. E_d is the electricity consumption. U denotes the term benefits which is accounted in terms of money. The benefit earned by the consumer as per the above curve can be written in terms of equations as:

$$U = \sum_{t=1}^{T}[(c1 + b1 * \Delta Pd_t + a1 * \Delta Pd_t^2) \tag{37}$$

ΔP_t^d is a free variable which can be constrained by minimum and maximum limit as follows:

$$\Delta P^{d,\min} \le \Delta P_t^d \le \Delta P^{d,\max} \tag{38}$$

$\Delta P^{d,\min}$ is the minimum demand met by the flexible load and $\Delta P^{d,\max}$ is the maximum demand met by the flexible load. Here $c1$, $b1$ and $a1$ are the constants.

4.3.2.1 Objective Function

The objective function is cost minimisation problem. Total cost of power procurement is given as $C^{\exp}$,

$$C^{\exp} = C^b + C^d + C^{RPO} + C^g \pm U + C^{UI} \tag{39}$$

Risk arising due to uncertain spot market price can be written as:

$$C^R = \sum_{t=1}^{T} \lambda_t^{di\,\mathrm{var}} (P_t^{di})^2 + \sum_{t=1}^{T} \lambda_t^{dp\,\mathrm{var}} (P_t^{dp})^2 + 2\sum_{t=1}^{T} \lambda_t^{\mathrm{cov}} (P_t^{dp})(P_t^{di}) \tag{40}$$

Where λ_t^{cov} is the covariance between IEX and PXIL spot market prices. There is positive correlation between both the spot market prices. The risk has been modelled using mean-variance approach.

Objective function can be written as:

$$\textbf{Minimize}_{\,P_t^{di}, P_t^{dp}, P_t^b, P_t^g, \Delta P_t, UI_t, u_t, v_t, c_t^s \quad \forall t} \quad C^{\exp} + \alpha\, C^{risk} \tag{41}$$

Where α is the positive weighing coefficient. Objective function is mixed integer no-linear type problem in nature. Overall objective is to minimize cost and risk. A trade-off between optimal cost and risk is obtained for different α values. At higher risk, minimum optimal cost is obtained.

4.3.2.2 Constraints

A. Demand balance

The consumer can satisfy its demand with different power purchase options available.

$$SI_t + UI_t = P_t^g + P_t^b + P_t^{di} + P_t^{dp} \qquad (42)$$

$$Pd_t + \Delta Pd_t = SI_t + UI_t \qquad (43)$$

Here SI_t is a variable which helps in scheduling the demand. Total power procurement planning for the time period T can be written as

$$\sum_{t=1}^{T} SI_t + \sum_{t=1}^{T} UI_t \geq P^T \qquad (44)$$

B. Self Generation Constraint

These constraints are given in equations (31)-(34).

C. UI constraints

Constraints on the UI_t can be expressed based on the deviation settlement mechanism as

$$-\delta * SI_t \leq UI_t \leq \delta * SI_t \qquad (42)$$

δ is the percentage of deviation caused if SI_t has been scheduled.

4.4 Modelling Summary

Mathematical modelling for the short term planning model for the consumer considering two different cases has been presented in the above sections. Both the models differ in their constraints and problem statement but the objective is same i.e. cost and risk minimisation. Uncertainty handling using mean-variance tool has been explained briefly. This developed mathematical model has been solved using GAMS and the results are analyzed in the next chapter.

CHAPTER 5. CASE STUDY RESULTS AND ANALYSIS

Mathematical model presented in the last chapter represents the optimal planning model for a large consumer participating in the short-term electricity market in India. This model requires some input values like the contract price of a bilateral contract. These input values can either be assumed or can be taken from the practical information. This chapter deals with the practical case study conducted for running the mathematical model and analysis of the outcomes. A large consumer has been considered in the western regional grid who is participating in the short-term electricity market in India. It can purchase electricity from the bilateral contracts, day-ahead contracts or self-generate the electricity. It is an obligated entity for RPO. Following sections cover the study conducted in the Indian case, applying it on the mathematical model and interpreting the results.

5.1 Assumptions

Assumptions taken in the program are as follows:

a) Actual demand of the consumer has been assumed cyclic with some percentage of flexibility.
b) FiT contracts are the long term contracts, but here they are considered for short term planning for RPO modelling.
c) RECs are traded in the market and market clearing price is decided so there is uncertainty in the price of REC considered. But here this uncertainty has not been considered although the price of RECs has been the average of the past values.
d) Policy change issues have been neglected.
e) Pool prices follow normal distribution curve.
f) Already existing system imbalances have been assumed.

5.2 Case 1

Western regional grid scenario has been considered for the planning model. The open access consumer has some percentage of its demand flexible. This consumer procures electricity from bilateral contracts, FiT contracts, DAM contracts through PXs and self-generation. UI transactions are also accounted as part of procurement. RPO for the month is fulfilled. Historical information of the UI rate has been considered. Planning period is one month with 672 hourly trading intervals. Following are the data related to this case.

5.2.1 Demand

The actual demand of the large consumer varies between 990 MW and 1140 MW as shown in Figure 5.1. It follows the same pattern every day. Flexibility in the demand of the consumer is 12 % or more than that of the actual demand. Minimum monthly demand limit is 660000 MW.

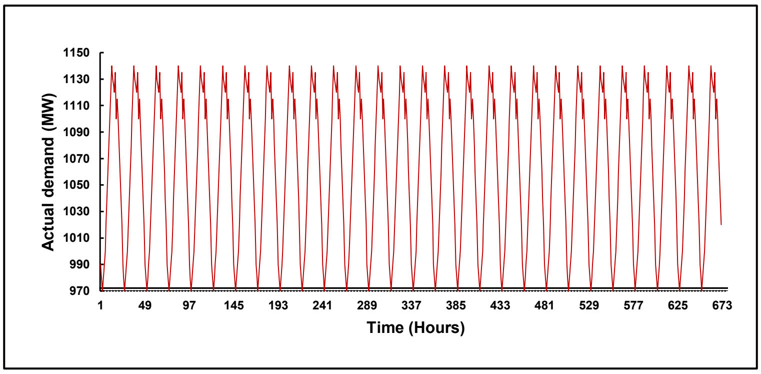

Figure 5.1 Electricity Demand of the Consumer in the Month

5.2.2 Spot Market and DSM

Spot market price data has been taken from the IEX website [35]. Historical data for the month of February has been taken for the past five years has been taken. Figure 5.2 shows the expected UI rate and expected spot market price. UI rate has been taken from the Western Regional Load Dispatch Centre (WRLDC) website [36]. Average standard deviation for UI rate and spot market price is 1255.349 Rs. /MWh and 692.4845 Rs. /MWh respectively.

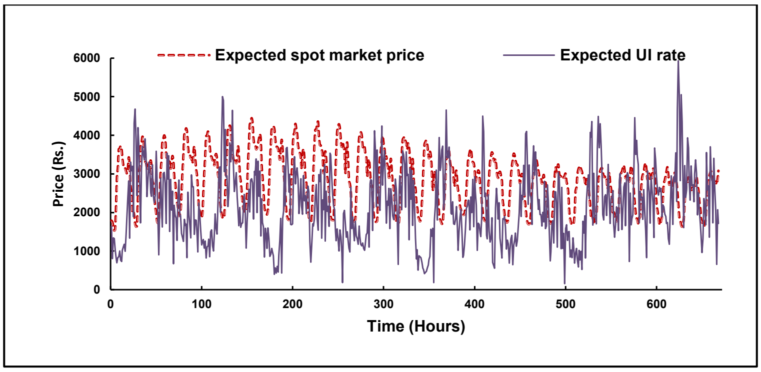

Figure 5.2 Expected UI rate and Spot Market Price

Figure 5.3 shows the correlation between UI rate and spot market price with their variances. Both positive and negative correlation exists with a random and intricate pattern in the time interval.

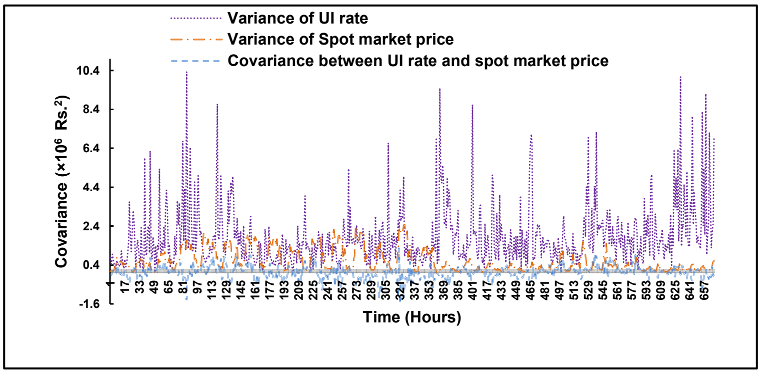

Figure 5.3 Covariance between UI rate and Spot Market Price

The variance of the UI rate is more random and larger than that of spot market price. This shows that the uncertainty of UI rate is higher and should not be neglected by the consumer while planning for procurement.

5.2.3 Bilateral Market

The consumer has one bilateral contract. Price and volume data for the available bilateral contract is shown in Table 5.1.

Table 5.1 Price and Volume Data for Bilateral Contract

	Price (Rs./MW)	Min. Volume (MW)	Max. Volume (MW)
I Week	2600	30	600
II Week	2800	30	600
III Week	3000	30	600
IV Week	2900	30	600

5.2.4 Self-Generation

One self-generation unit is available at the site. Data for self-generation unit is given in Table 5.2.

Table 5.2 Data for Self-Generation Unit

Capacity	120 MW
Minimum power output	20 MW
Ramping limit (up/down)	80 MW
Quadratic Cost	0.6 Rs./(MW)^{2}h
Linear Cost	2700 Rs./MWh
No-load Cost	2000 Rs.
Startup Cost	1000 Rs.

5.2.5 RPO

FiT has been considered as 5000 Rs./ MWh and RPO has been considered as 10 % depending on the values present in the states of western regional grid. Maximum limit on power procurement from FiT has been considered as 700 MW. Non-solar REC price from the last five years (2011-2015) has been assumed as Rs. 1870. Maximum number of RECs that can be purchased by the consumer is 50,000.

5.2.6 Results

To find the optimal results, the mathematical code has been solved by SBB-CONOPT under GAMS by Intel ® Core™ i3 CPU, 2 GHz and 4 GB RAM computer with an average solution time of 180.34 s. Following subsections represent the results and discussions on them.

5.2.6.1 Efficient Frontier

Figure 5.4 shows the efficient frontier for the case 1.

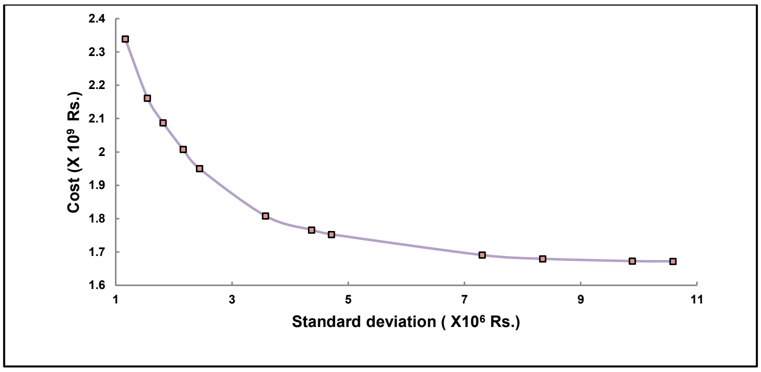

Figure 5.4 Expected Cost v/s Standard Deviation

Efficient frontier shows the purchasing from different options or portfolio with different values of risk. Values of risk (standard deviation) are plotted on the x axis and values of optimal cost have been plotted on the y axis. This curve shows the optimal cost for different values of risk. Dotted points denote the weighing factor or alpha. Meaning of this curve is that the risk taking consumer needs to invest less or has less cost of purchasing, on the other hand, a risk-averse consumer needs to invest more or has more cost of purchasing. As evident from the Figure, as risk increases, optimal cost decreases, and vice versa. Value $\alpha = 0$ denotes the highest value of risk and as α increases, risk decreases. The consumer can choose the value of α according to his preferences for the planning strategy of power procurement.

5.2.6.2 Power Procurement

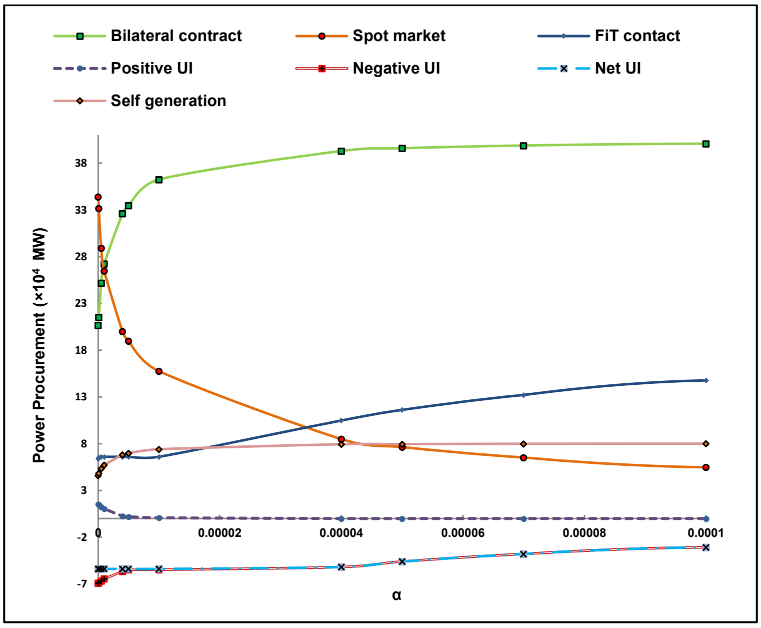

Figure 5.5 Power Procurement from Different Options at Different Values of alpha

Figure 5.5 shows the power procurement from the different options at different values of α. At higher values of risk i.e. lower values of α, power procurement from the spot market is more. This is because spot market is a risky asset due to uncertain price. But this procurement decreases with increasing values of α .On the other hand, bilateral, FiT and self-generation are the non risky assets, so procurement from these options increase with the increasing values of α i.e. decreasing risk. Procurement from UI can be both negative and positive. UI is also a risky asset. Procurement from it also decreases with increasing values of α. Both negative and positive procurement decreases. The positive value of UI occurs during periods of low UI rates while negative UI suggests reducing consumption up to demand flexibility limit, in order to reduce cost.

The sum of both the values of UI *i.e.* UI net is same till α =0.00004 and starts decreasing afterwards. This is due to lower values of α, that makes procurement from risky spot market and value of UI relatively more than other options. This also results in less investment. The reason for constant value of UI net is due to constant monthly power procurement up to α = 0.00004 which is result of constant monthly FiT procurement up to α =0.00004. For values of α less than 0.00004, power procurement from FiT contracts is less due to more risky behavior and so RECs are purchased for satisfying RPO constraint. RECs purchase is 2019 for $\alpha = 0$ and 741 for value of $\alpha = 0.0000001$.When α increases beyond α =0.00004, risky behavior decreases exponentially and so power procurement from other sources increase.

5.2.6.3 Scheduled Demand

The procurement strategy suggests consumer to shift its demand from scheduled one. Figure 5.6 shows the revised demand of the consumer for α =0. This helps to attain minimum cost position by the decision maker. Fig. 5.7 shows comparison in demand alteration for α =0 and $\alpha = 0.000004$. For clarity in representation, results for only two days are shown in the two Figures, though similar results are obtained for whole planning period.

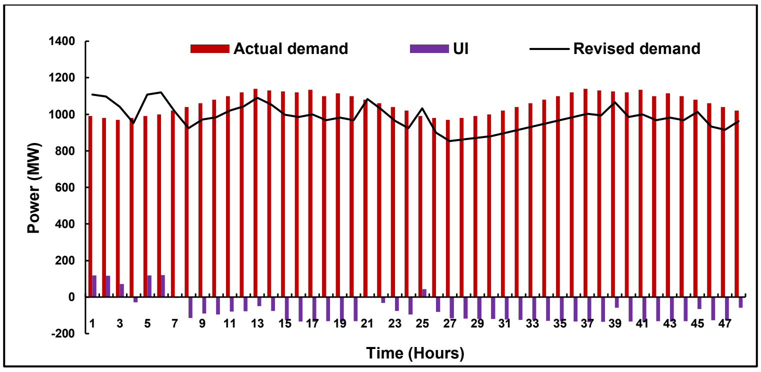

Figure 5.6 Demand Pattern for alpha =0 for 48 hours

Revised demand is the sum of the actual demand and unscheduled deviation (UI). Negative UI values signify decrease in actual demand while positive UI value represents increased actual demand.

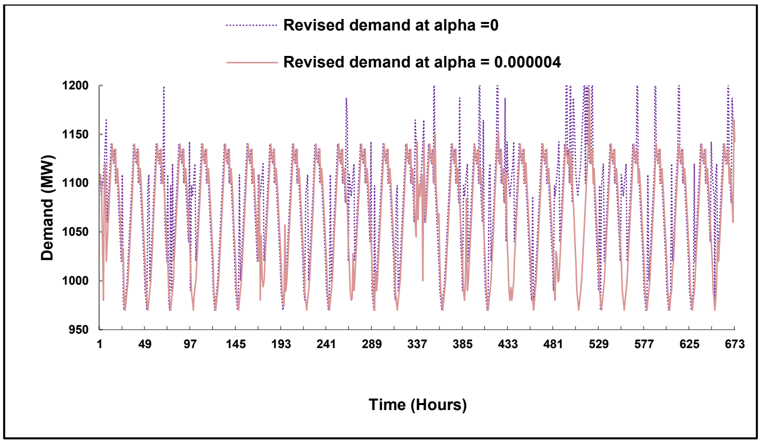

Figure 5.7 Demand pattern for alpha=0 and alpha =0.000004

Revised total monthly demand is 660000 MW up to α =0.00004, which then increases to 698348.9MW till α =0.0005. Revised total monthly demand reduces with percentage reduction 2.2% (α = 0.0005) to 7.5 % (α = 0) in the actual total monthly demand. The initially increasing and then reducing total demand represents consumers increasing preference for risk. The increasing demand represents negative correlation between DAM and UI prices. Due to UI value, flexibility introduced in demand for the consumer varies from +2.1% to -9.7%.

5.3 Case 2

The case presented above considers uncertainty of UI rate using the past information. As UI rate are very unpredictable and can result in a large amount of penalty charge at real time, the effect of scheduling strategy of a consumer on the real-time frequency cannot be overseen. This case investigates the result of planning model of the consumer on the real time. Here consumer is capable of effecting grid frequency significantly. This large consumer participates in the short-term electricity market to purchase from bilateral contracts, DAM, and self-generation for a week. There are two DAMs; one is through IEX and another one is through PXIL. Following are the input data from the case study done on the large consumer in WRLDC. Total trading intervals are 168 hours. Results have been analyzed in the later sections.

5.3.1 Demand

The demand of the consumer varies between 970 MW to 1140 MW as shown in Figure 5.8. It has 40 % of flexible loads which can be used for increase or decrease in the demand. On increasing the demand using the flexible demand, consumer is having benefits which are 500 Rs./MW.

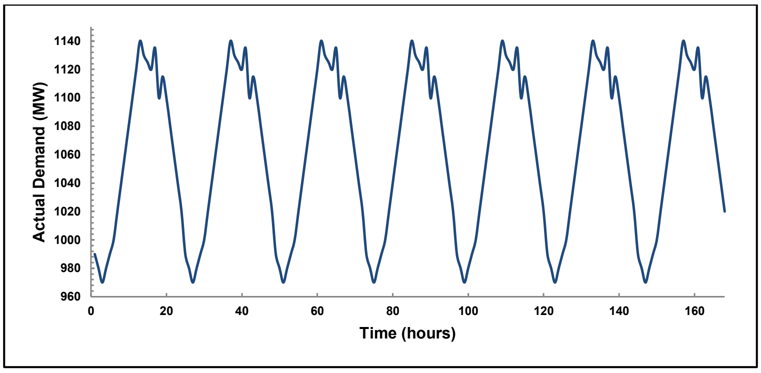

Figure 5.8 Actual Demand for the planning period

5.3.2 Bilateral contract

The consumer has one bilateral contract. Price for the available bilateral contract is 3000 Rs./MW. The minimum volume of power that can be purchased is 30 MW while maximum volume of power that can be purchased is 800 MW.

5.3.3 Self Generation

One self generation unit is available at the site. Data for self-generation unit is given in Table 5.3.

Table 5.3 Data for Self-Generation Unit

Capacity	120 MW
Minimum power output	20 MW
Ramping limit (up/down)	80 MW
Quadratic Cost	0.6 Rs./(MW)^{2}h
Linear Cost	2700 Rs./MWh
No-load Cost	2000 Rs.
Startup Cost	1000 Rs.

5.3.4 Spot Market

Spot market data has been taken from the IEX [35] and PXIL website [37] for the ten consecutive weeks in the year (2011) for the justified interpretation. Figure 5.9 shows the average price for the planning period for both the markets. Average price for IEX spot market and PXIL spot market is 3154.307 Rs./MW and 3182.883 Rs./MW respectively.

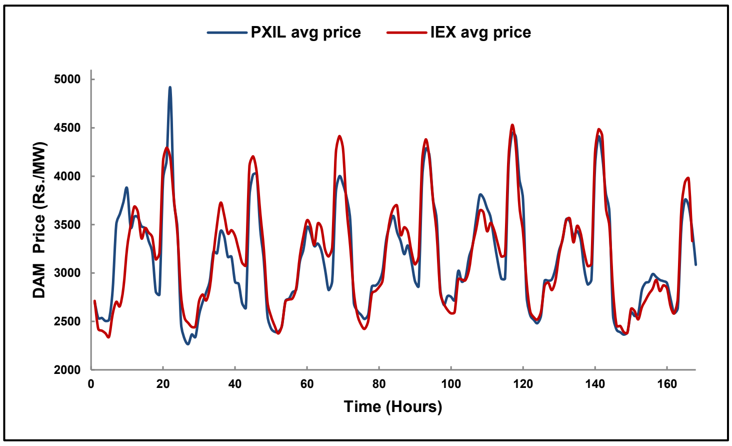

Figure 5.9Average IEX and PXIL Market Price

Figure 5.10 shows the variances of both the markets and covariance between them for the planning period. Average covariance of IEX spot market and PXIL spot market is 671751.2 $(Rs./MW)^2$ and 492060.2 $(Rs./MW)^2$ and average covariance is 394387.7 $(Rs./MW)^2$. Positive covariance exists between the prices of both the markets.

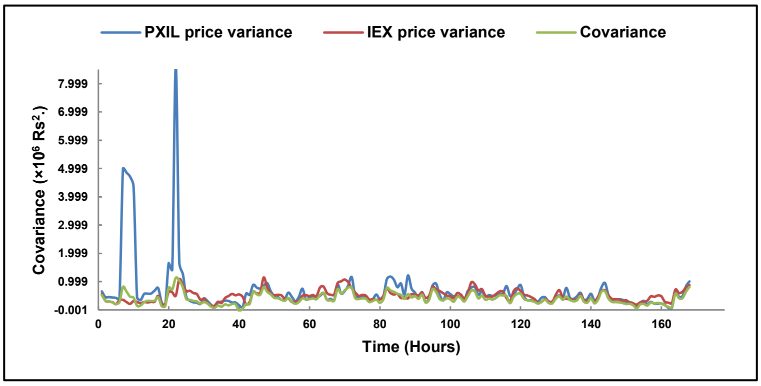

Figure 5.10 Covariance between IEX and PXIL Market Price

5.3.5 RPO

Here market mechanism is not considered for the RPO. Instead, a fixed cost is added in the cost function. 10% of power purchase of the consumer for the planning period is considered from the renewable energy sources. The cost of purchasing for the RPO is considered as 5000 Rs./MW.

5.3.6 Grid Frequency

Grid frequency is being calculated from the equation 35 as given in chapter 4.

$$f_t = 50 - \frac{L_t - [G_t - UI_t]}{FR * L_t}$$

Frequency fall ratio from the literature [38] can be found as 4%. Total system demand as Indian grid system has been considered as 100 GW. Total generation for the nominal grid frequency has been considered as 100 GW. Some deviations are considered in the system.

5.3.7 Results

The results obtained from running the model with input data from case 2 are listed below. The mathematical code has been solved by SBB-CONOPT under GAMS by Intel ® Core™ i3 CPU, 2 GHz and 4 GB RAM computer with an average solution time of 46.38 s.

5.3.7.1 Efficient Frontier

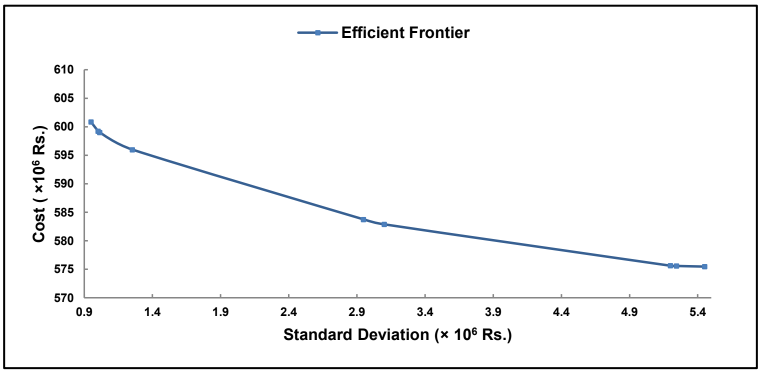

Figure 5.11 Cost versus Standard deviation

Figure 5.11 shows the efficient frontier for the case 2. The cost of purchasing from the given options decreases with the increase of standard deviation i.e. risk. So a risk taking consumer can purchase electricity at relatively less cost as compared to the risk-averse consumer. At α =1e-7, risk decreases significantly to α =9e-7. Similar decrease happens at α =1e-6 to α =4e-6. The curve starts becoming constant after α =5e-5.

5.3.7.2 Power Purchase

Figure 5.12 shows the power purchase from different options for the case 2. Power allocation for the risky assets like IEX market and PXIL market both start decreasing as the value of α starts increasing that is risk starts decreasing. So the purchase from these markets is maximum at α =0. On the other hand, power purchase from other options like bilateral contract and self-generation starts increasing as the value of α starts increasing. These become constant at the higher values of α . UI allocation is negative signifying demand decrease for the planning period.

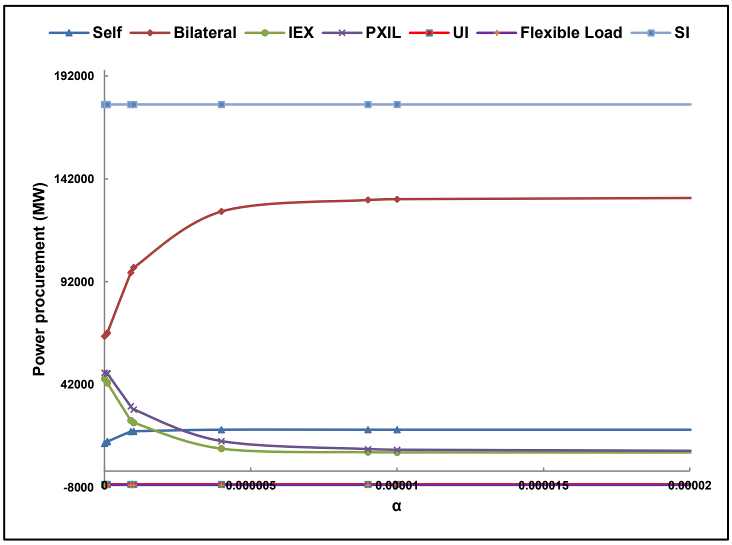

Figure 5.12 Power Purchase from Different Options

Despite having benefits from increasing the demand using the flexible loads, results are indicating the decrease in the demand using the flexible loads because of lower benefits which can not counter the increase in cost due to the more allocation in the existing options as evident from the power balance equation 42 and equation 43. Scheduled demand is less than the actual demand and is constant as the UI allocation and flexible loads for each value of α . Effects of changing the benefits can be seen in the section 5.3.7.6.

5.3.7.3 UI allocation

The UI allocation depends on the grid frequency and can be seen in the following Figures for the planning period. Figure 5.13 shows the frequency variation and UI allocation for the planning period. As linear UI curve has been considered for the work instead of the piecewise UI curve, one can see the effects of linearity of frequency on the UI allocation. When frequency is below 50 Hz, UI allocation is positive or less negative at that time. It means the consumer is purchasing more in the planning period so that over withdrawing does not occur at the worse grid conditions. On the other hand, when grid frequency is above 50 Hz, UI allocation is more negative. This shows that the consumer is purchasing less at the better grid conditions such that over withdrawing at the worst possible scenario will provide less penalty.

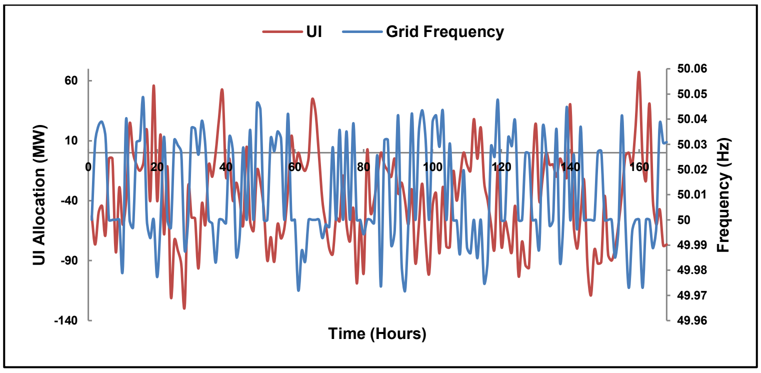

Figure 5.13 Frequency and UI Allocation for the Planning Period

Frequency variation with the UI rate can be seen in the Figure 5.14. These are independent of values of α . Effect of linearity is visible in both the curves. UI rate has been calculated from the frequency (equation 35) which is a linear relation.

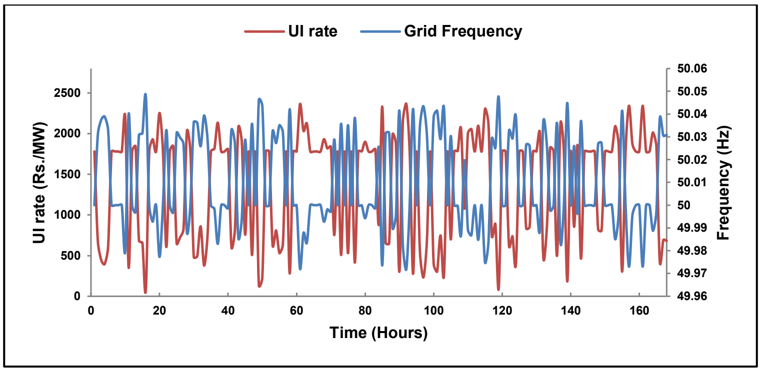

Figure 5.14 Grid Frequency and UI rate for the Planning Period

5.3.7.4 Frequency improvement

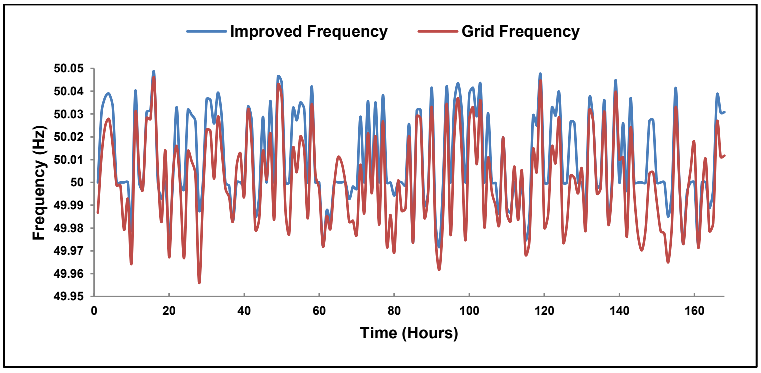

Figure 5.15 Frequency Balancing

Figure 5.15 shows that the grid frequency can be improved by the consumer at the real time. The red line shows the grid frequency existing in the real system having imbalances. Blue line shows the frequency which has been improved after creating the planning model for the consumer. This can be understood in this way that when grid frequency is falling at dangerously low level, then consumer can under withdraw its demand and can help in improving it at the real time. The consumer has already shifted its demand such that at these low value of frequency, consumer has increased its demand by procuring more in the planning period which can be decreased at the real time using the flexible loads. On the other hand, consumer has decreased its demand by procuring less in the planning period for the frequency higher than the grid frequency. Consumer need not take any action in such cases because grid frequnency is in the specified band.

5.3.7.5 Procurement Cost

The cost allocation with respect to value of α =0 has been shown in Figure 5. 16. Cost allocation for the IEX and PXIL market follow the relatively opposite pattern. Cost allocation of bilateral market and self-generation follow the same pattern. Their purchasing cost is almost constant for some trading intervals. This variation is coming independent of frequency.

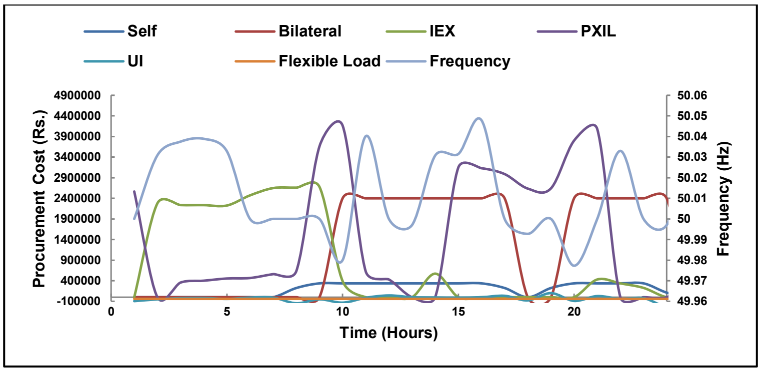

Figure 5.16 Cost Allocation for alpha =0 for a Day

Cost allocation for α =9e-07 is given in the Figure 5.17. Cost allocation for UI and flexible loads does not change with the change in the risk. But it changes for other options. Purchasing cost from PXIL market is again higher than the IEX market but is less than the previous value of α . Procurement cost for the self-generation is maximum for most of the time thus self-generation unit running at maximum power output most of the time. Bilateral cost procurement has been less than the PXIL market procurement cost.

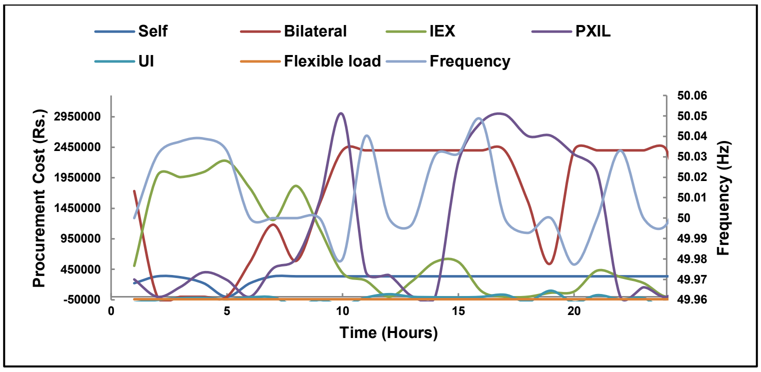

Figure 5.17 Cost Allocation for alpha = 9e-07 for a day

5.3.7.6 Sensitivity Analysis

This analysis is done for the effects of flexible loads on the problem model. The benefits have been increased and its effect on the allocation from the all the options has been seen. It has been also seen that how this effects the frequency. The following curve shows this effect.

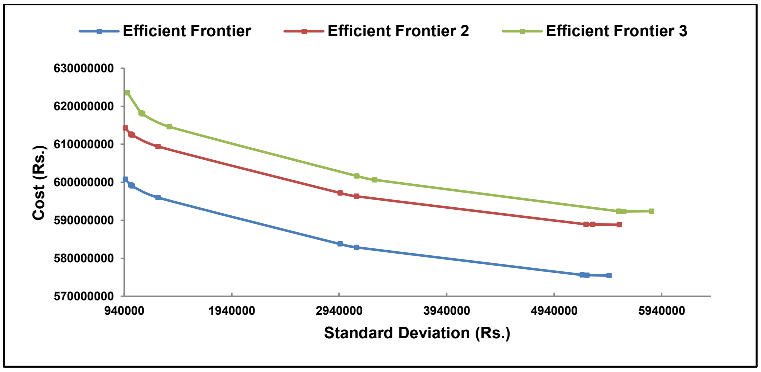

Figure 5.18 Efficient Frontiers for Different Benefits

Figure 5.18 shows the efficient frontier for three different benefits value. Benefits are increasing from efficient frontier 1 to 3. Risk and Cost for a particular α value are increasing on increasing the benefits. The increase in cost even after increasing benefits is due to increase in the procurement due to flexible loads. Risk also increases due to more procurement from the DAMs. This shows that the even consumer gets benefits in terms of money by having flexible loads, but more benefits will also result in higher procurement due to increase in demand. UI allocation varies with the risk values as evident in the following Figures.

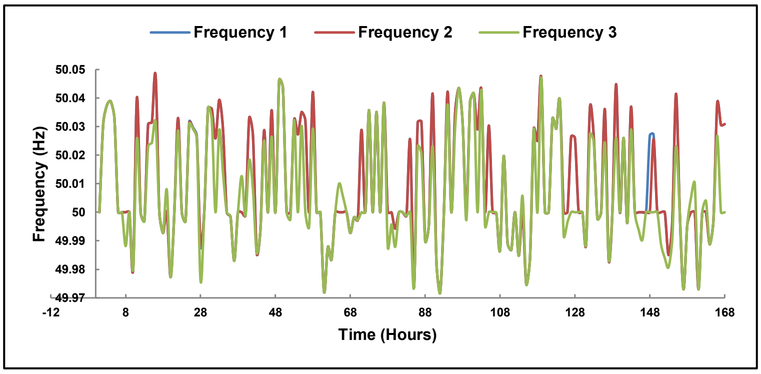

Figure 5.19 Frequencies for Different Benefits

Figure 5.19 shows the frequency variation for different benefits for α=0.. Up to a particular value of benefit, there is not much effect but this effect starts showing after a particular value as seen in the frequency 3. The effect is more evident in the frequency values above 50 Hz. The frequency is shifting more towards the nominal grid frequency. This is due to the change in the value of positive UI allocation.

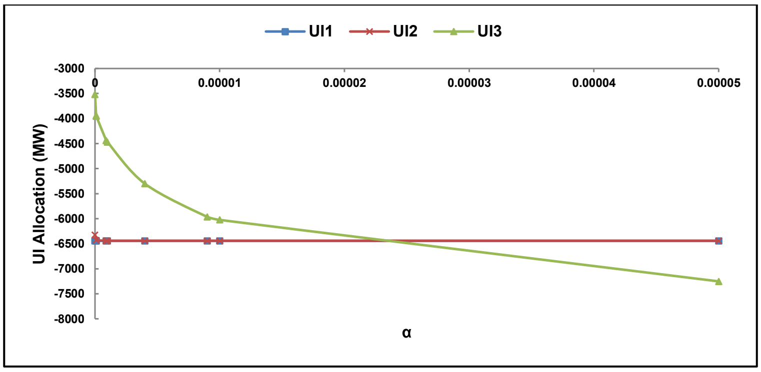

Figure 5.20 UI Allocations for Different Benefits

Figure 5.20 shows the UI allocation for different values of α for different benefits. Due to increase in demand at lower values of α with increase in use of flexible loads, UI allocation is less at lower values of α for the higher benefits. But this UI allocation increases with decrease in risk values. This can be explained by the fact that it is easy to increase the procurement at higher risk due to available DAMs. But as the risk decreases, procurement decreases due to higher cost as evident from the efficient frontier curve in Figure 5.19.

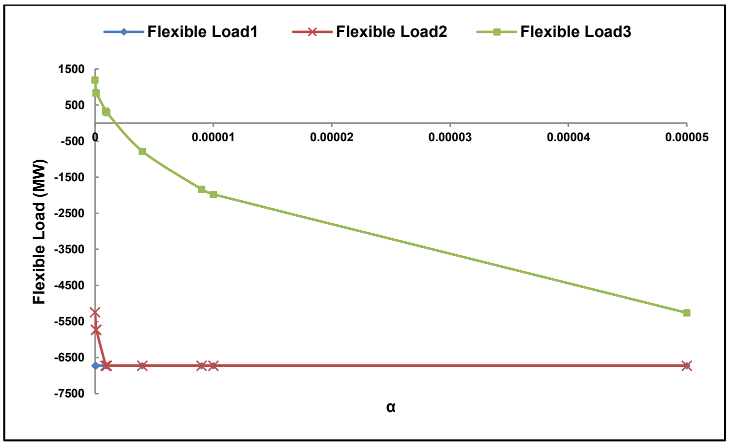

Figure 5.21 Flexible Loads for Different Benefits

Flexible loads start showing changes for the risk values after a definite increase in the benefits. Upto a particular value of α, there is increase in the demand using the flexible loads as can be seen in the Figure 5.21. For the flexible load 3 curve, this value of α is 0.000001.

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CHAPTER 6. CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

The main aim of study was to develop a planning model for an open access consumer in India to participate in the short-term electricity market. The consumer had different options available for power purchase. These options were bilateral contracts, DAM contracts and had an available self-generating unit. The uncertainty of grid frequency and DAM price were considered along with obligations for renewable purchase. The planning model for two different cases has been developed in this work. The two cases differ in the consumer's role in the impacting the grid system.

In the first case, four different power procurement options were considered for the consumer which included bilateral contract, self-generation, DAM, and FiT contract. RPO was fulfilled through the FiT and the REC purchase. DSM was also accounted in the short term power procurements. Planning model was developed for a month taking historical information for the UI and DAM price. As consumer had negligible influence on the grid frequency, UI rate was calculated from the past information. Risk included variances due to UI rate and DAM price. The flexible demand of the consumer was considered. The results were shown using plots for different values of risk weighing factor. The consumer can schedule its demand before a month for optimal power purchase avoiding the penalty for the over withdrawal. Results indicate that procurement from DAM and with positive and negative value of UI is more at lower values of risk aversion, though it decreases with risk aversion and shifts towards risk-free options. The results suggest reducing consumption at real time to get minimum cost, though this demand alteration is higher for lower risk aversion levels and reduces with increasing risk aversion. UI value has introduced notable demand flexibility for the consumer.

In the second case, planning model was developed for the consumer for a week using options like bilateral contract, self-generation and multiple DAM. As consumer's power withdrawal from the grid can largely affect it, UI rate was calculated from the grid frequency using UI curve. The consumer had flexible loads to absorb the changes in the actual demand. The results are shown for different plots for different values of risk weighing factor. As compared to the first case, risk is arising due to the uncertain DAM price only. The consumer can schedule its withdrawal before a week for optimal power purchase. Results indicate the procurement from DAMs higher at higher risk values which decrease with decreasing risk. Procurement from bilateral contracts and self-generation increases with the increasing risk values. UI value and use of flexible loads remain unaffected with the risk until a noticeable benefit with increasing consumption using flexible loads or a deterring penalty with decreasing consumption using flexible loads come into the picture. Results show that using the flexible loads, consumer can help in managing the grid frequency. Real-time system deviations worsening the grid frequency can be improved by the consumer at the real time.

6.2 Future Scope

The study conducted for planning a strategy for a large consumer in India in short-term electricity market has provided substantial results which can be implemented practically for an Indian case. Not much work on the electricity market for the Indian open access consumers has been done. Based on the experience gained during this work, it is suggested that more work in the following areas can be done.

- Risk approach can be handled using more prominent techniques like Value-Added Risk (VaR) and CVar.
- Both demand and price uncertainty for a distribution company can be handled simultaneously using IGDT approach.
- A case of hypothetical retailer can be taken in place of open access consumer depending on the policy introductions and reforms in the Indian Electricity Sector
- UI mechanism can be treated more as an ancillary market and can be modelled for the participation of large consumers in India for grid balancing.

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