CRANFIELD UNIVERSITY

XABIER MARTÍN SANTIAGO

# STOCHASTIC ANALYSIS OF ELECTRICITY PRICES IN INDIA FOR HIGH RENEWABLE ENERGY PENETRATION

SCHOOL OF ENERGY, ENVIRONMENT AND AGRIFOOD
Energy Systems and Thermal Processes

MSc
Academic Year: 2015 - 2016

Supervisors: Giuseppina di Lorenzo,
Jesus Nieto Martin

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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

# ABSTRACT

India is currently a major energy consumer due to its daily increase of population. As an effect of that, its power system infrastructure lacks of resources and capacity to provide the population with a reliable access to electricity. For instance, losses in transmission and distribution are of around 20% of the generated electricity. Its energy generation mix is mainly based on national coal, which possesses a low quality and low calorific value, being therefore inefficient and increasing the CO2 emissions to the atmosphere. As result of newly introduced energy policies, the country is looking to increase the generation from renewable sources, so as to help climate change mitigation. This thesis has focused on finding a proper energy mix with a higher renewable penetration that will, at the same time, maintain reasonable electricity prices. For this purpose, a stochastic approach has been taken, where data has been expressed as probability distributions, to account for the uncertainties in the input parameters.



Keywords: *Monte Carlo simulations, energy mix, energy policy, variability, model, forecast*

Word count: 7483

# ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisors for their continuous guidance and all the time they have dedicated to help me with this project. To Giuseppina di Lorenzo, for all the help and for encouraging me on moving to this topic. To Jesús Nieto Martín, for all the new insights he has given me about the energy market and for bearing with me not only during the thesis, but also during the group project.

Secondly, this would not have been the same without all the amazing people I have met throughout the Cranfield journey. A very big thank you to *Chilver 3* and *Cranfield Remembers*, who have made each moment special. You have helped to turn what seemed to be a university in the middle of nowhere into a home where I have spent an amazing year that has definitely changed my life for good.

I would also like to thank the University of the Basque Country for giving me the opportunity of coming to Cranfield.  Furthermore, to my friends in Vitoria and Santander, who have been key supports at every time.

Finally, my sincerest gratitude goes to my family for their support and for being there in the difficult moments. Thanks to my parents, Emilio and Marivi, for the values they have always transmitted me and for being the perfect example of hard-working people. Thanks to my brother Mikel, for putting up with me for the last 24 years. Thanks to my brother Victor, for being an example of a successful engineer whose footsteps I will follow. Last but not least, thanks to my grandparents for the invaluable support and for always wanting the best for their grandchildren.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ARMA | Autoregressive Moving Average |
| CEA | Central Electricity Authority |
| CDEC-SIC | Centro de Despacho Económico de Carga del Sistema Eléctrico Central |
| CSP | Concentrated Solar Power |
| EA | Electricity Act |
| FTR | Firm Transmission Rights |
| GARCH | General Autoregressive Conditional Heteroscedasticity |
| GHG | Greenhouse Gases |
| GDP | Gross Domestic Product |
| IPP | Independent Power Producers |
| IT | Information Technology |
| IEA | International Energy Agency |
| LDC | Load Dispatch Centre |
| MC | Monte Carlo |
| NADCC | National Action Plan on Climate Change |
| RE | Renewable Energy |
| REC | Renewable Energy Certificate |
| RECAI | Renewable Energy Country Attractiveness Index |
| RPO | Renewable Purchase Obligation |
| SEB | System energy Board |
| T&D | Transmission and Distribution |

# Stochastic Analysis of Electricity Prices in India for High Renewable Energy Penetration

***X. Martín Santiago[1], G. Di Lorenzo[1], J. Nieto-Martín[2]***

[1] *School of Energy Environment and Agrifood, Cranfield University, College Rd, Cranfield, Bedfordshire MK43 0AL*

[2] *School of Aerospace, Transport and Manufacturing, Cranfield University, College Rd, Cranfield, Bedfordshire MK43 0AL*

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## Abstract

India is currently a major energy consumer due to its daily increase of population. As an effect of that, its power system infrastructure lacks of resources and capacity to provide the population with a reliable access to electricity. For instance, losses in transmission and distribution are of around 20% of the generated electricity. Its energy generation mix is mainly based on national coal, which possesses a low quality and low calorific value, being therefore inefficient and increasing the CO2 emissions to the atmosphere. As result of newly introduced energy policies, the country is looking to increase the generation from renewable sources, so as to help climate change mitigation. This thesis has focused on finding a proper energy mix with a higher renewable penetration that will, at the same time, maintain reasonable electricity prices. For this purpose, a stochastic approach has been taken, where data has been expressed as probability distributions, to account for the uncertainties in the input parameters.

Keywords: *Monte Carlo simulations, energy mix, energy policy, variability, model, forecast*

# 1 INTRODUCTION

## 1.1 Background

In spite of India being a major energy consumer worldwide, its energy sector is still unable to provide energy security to the whole population, due to its ineffective and poor power system, along with the low investment obtained from external parties [1].

As a result of this situation, in the recent years the government has pushed different policies to make sure the three main energy objectives are developed [1]: energy access, energy security and climate change mitigation. This thesis will focus on the latter, and more specifically on the introduction of a higher percentage of renewable energies (RE) in the energy mix of the country to reduce emissions. Instead of following the much-used deterministic approach, a stochastic one will be applied, using probability distributions to account for the uncertainties that may exist. Overall, in this report an energy mix with high penetration of RE that minimizes the electricity price will be sought.

## 1.2 Research gap and motivation

Many studies regarding prediction of electricity prices have been carried out using a deterministic approach, but this project is motivated by the use of stochastic methods to account for the uncertainties in the input parameters. Also, being India a country with deficiencies in their power system, this report aims to find ways of improving it, being able to cope with a higher percentage of renewables.

## 1.3 Aim and objectives

The aim of this master thesis is to find a proper energy mix for India with a higher renewable energy penetration while still maintaining reasonable electricity prices to be able to grant electricity access to the population. The objectives to be achieved are:

- Select and justify the country of study, which is India as mentioned before
- Study of the power system of India, analysing the challenges to be faced and the objectives to be achieved by the energy policy.

- Define a methodology to model electricity prices using a stochastic approach
- Define different plausible scenarios for India and find the data for each of the scenarios
- Verify the model by fitting the results to a normal distribution
- Extract conclusions and propose further work to be developed to complement this analysis.

## 1.4 Report structure

This report is structured as follows. Section 2 shows a literature review about the energy context in India and the problems of integrating renewable energies, as well as stochastic methods for accounting uncertainties. Section 3 depicts the methodology of the problem, which encompasses the background on the power market and challenges and regulation that it faces and explanation of methodology. In Section 4 the results are displayed and analysed. Finally, conclusions and recommendations for further work are presented in Section 5.

# 2 LITERATURE REVIEW

## 2.1 Selection of location and energy context

For this study a fast developing country was chosen for analysing and contributing in a meaningful way to the public knowledge. Since many studies like this have been carried out for already developed countries, India, as a fast growth developing country, has very good characteristics in terms of potential for large integration of the renewable energy sector. India particularly is an investor friendly ecosystem due to the government having allowed up to 100% foreign ownership in Indian renewable companies [2]. Also, the new government has encouraged foreign investment in the renewable energy sector, where a considerable investment was done last year [3]. Another important investment is the one done by the World Bank Group, which consists of roughly 1$ billion, so as to scale up solar energy in India over 2017 [4].

Currently, the country has a huge potential for renewable generation (mainly solar and wind) that will be boosted by government incentives, which are explained later in the report. This will be translated into a reduction in the dependency on coal and gas, potentially leading to an increase of the work force and benefits such as the electrification of remote areas.

### 2.1.1 Power sector and energy mix

Impressive achievements in the power sector have been made in India in recent years [1], but it is still missing a crucial component for the future outlook: transmission and distribution infrastructures. Due to the lack of financial resources, utilities are unable of upgrading the ageing lines, which hinders meeting the obligations to purchase power from RE sources [1].

India is, undoubtedly, a country that mainly runs on fossil fuels to generate electricity. Coal takes the highest share of power generation capacity (60%), followed by hydro and gas. As shown in Figure 2.1, generation has increased significantly. Even though, India still faces a structural shortage of power that needs to be sorted out.

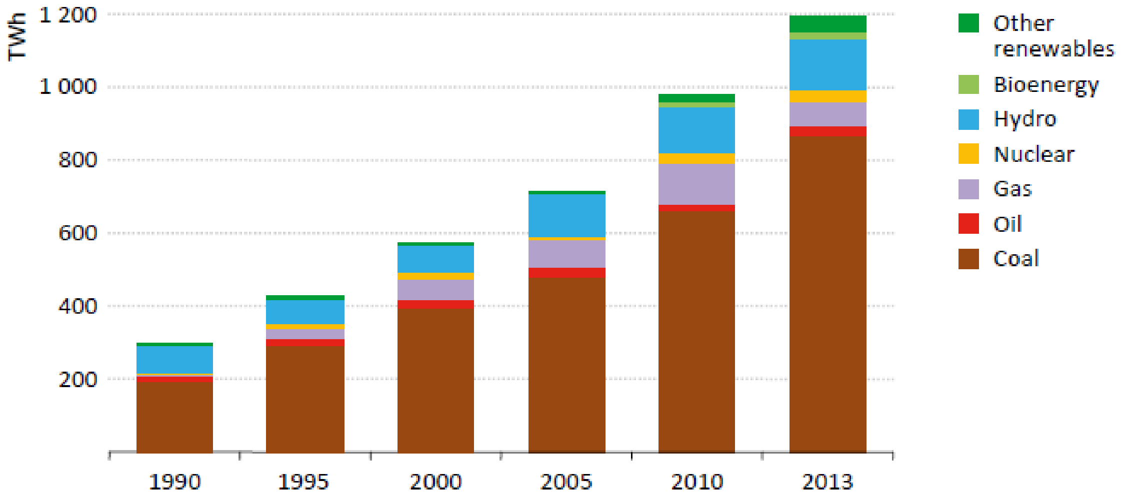


**Figure 2.1. Total electricity generation in India by fuel** [1]

Figure 2.2 shows the forecast for the energy mix in India. Coal will still play the biggest share in the generation sector, but its relative weight compared to RE will decrease notably. The share of RE will increase from a current 17% to 26%, which is certainly a promising figure.

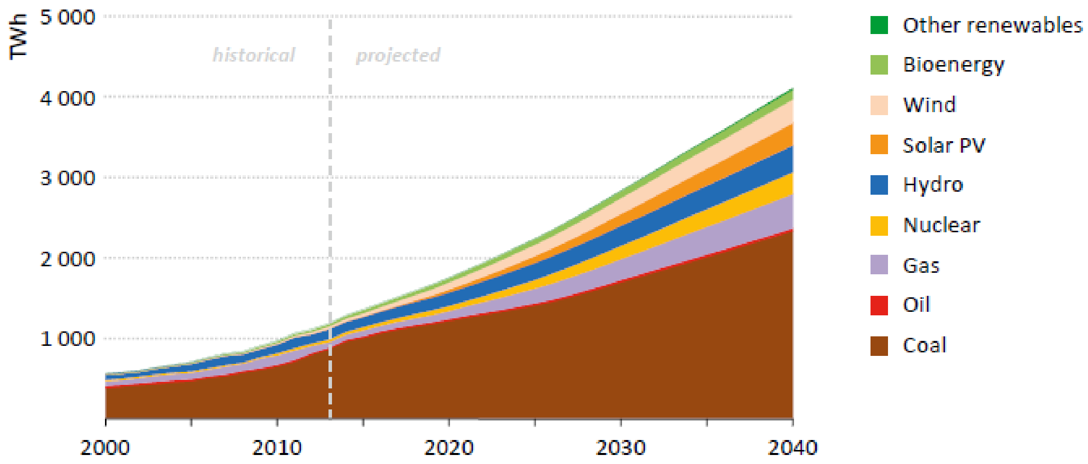


**Figure 2.2. Prospection for power generation in India** [1]

### 2.1.2 Current situation and prospects for RE

India has always had renewable energy as a very important component of their energy planning process. Renewable power generation capacity was of 26,920 GW in 2013, which accounts for around 12% of the total installed power capacity [5].

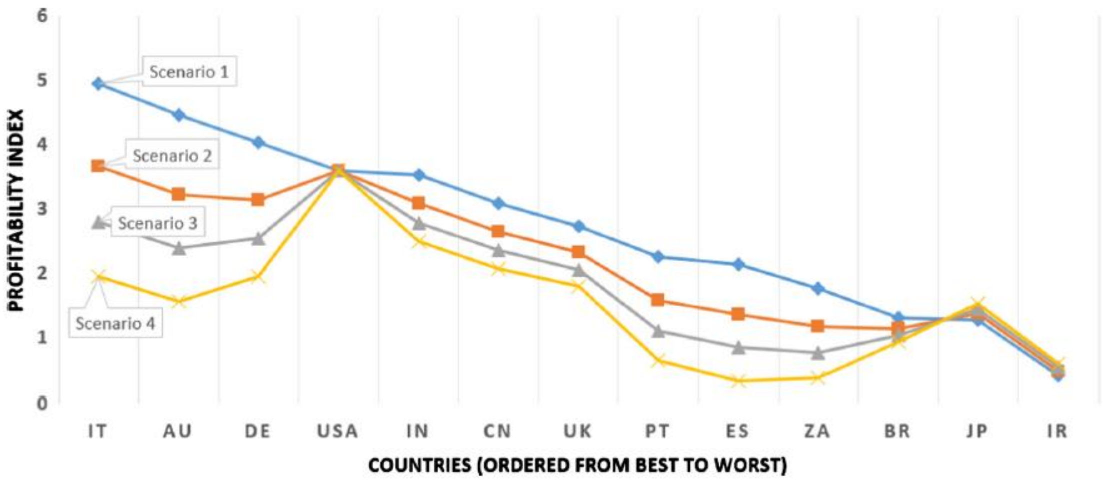


**Figure 2.3. Profitability index for selected countries** [5]

Analysing the figure shown above, it can be inferred that India is the first developing country in the rank of profitability index for RE, which means it will be a country worth to invest in. This is also supported by [6], where it is stated India is the second country in terms of CSP capacity and the fifth one for wind power and geothermal capacity. Solar energy potential is the highest with an equivalent energy potential of 6000 million GWh per year [7]. Small hydro power has been the oldest RE technology used in India and it has grown rapidly during the last decade [7].

Ernst & Young [8] ranked India in the 9th position according to the Renewable Energy Country Attractiveness Index (RECAI). Also, the growth of installed renewable capacity has been of around 18% as shown in Figure 2.4.

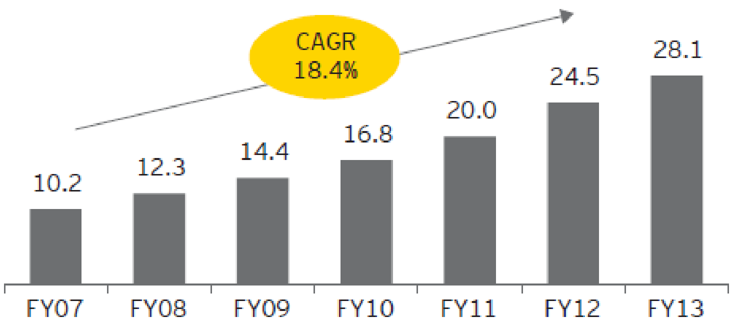


**Figure 2.4. Growth of installed capacity of renewable energy in India (GW)** [8]

### 2.1.3 Government drivers and regulatory framework

The key drivers that have motivated the growth in the country have been [8]:

- Government support: it is playing an active role in promoting the development and use of RE by offering various incentives.
- Climate change: India, being one of the most vulnerable countries to climate change, released a plan to fight against it. This plan promotes the adaptation, understanding and mitigation of climate change, energy efficiency and resource conservation.
- Increasing cost competitiveness of RE: equipment prices have fallen considerably as a result of innovation, increasing manufacturing scale and experience curve gains.
- Vast untapped potential: India holds a vast potential of RE resources which provides opportunities for establishing land-based RE generation as well as offshore wind farms.

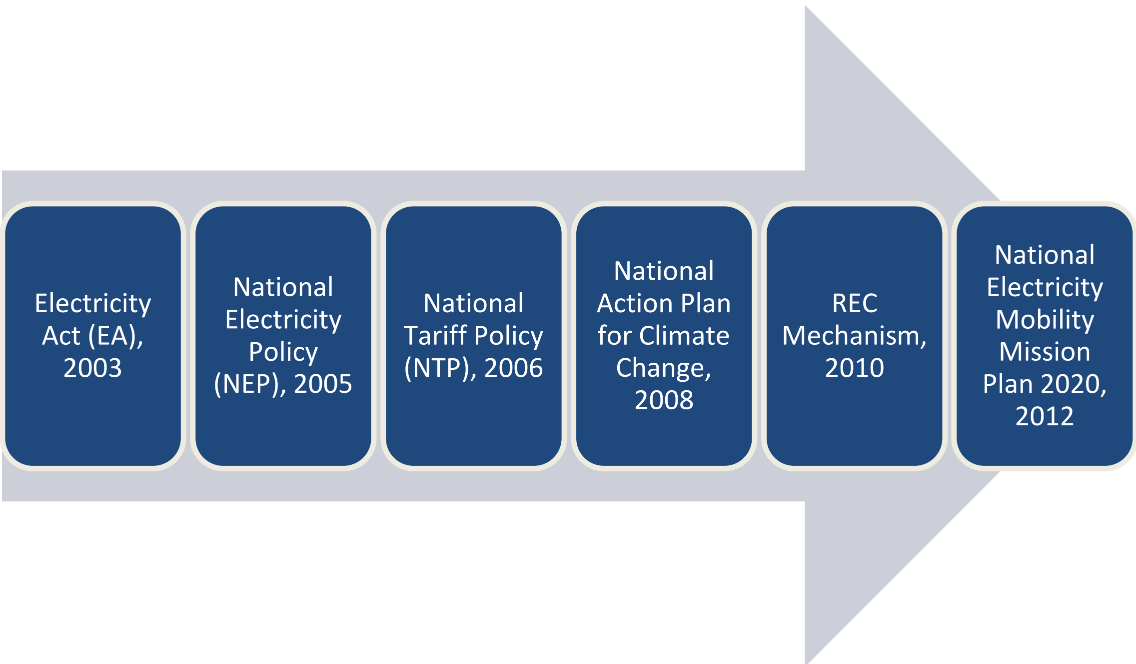


**Figure 2.5. Policies and regulatory framework for RE in India** [8] **&** [9]

The regulatory framework for RE in India has evolved as shown in Figure 2.5. The Electricity Act launched in 2008 was followed by the National Electricity Policy, in which capital reduction of RE is targeted through competition. The

Renewable Energy Certificate (REC) mechanism was included as a market mechanism to promote RE and ease the compliance of Renewable Purchase Obligations (RPO).

## 2.2 Indian electricity market

### 2.2.1 Introduction

The electricity sector in India has long experienced capacity shortfalls, poor reliability and quality of electricity and constant blackouts. This poor electricity supply is identified as a great impediment to economic growth [10]. India's electricity sector has mainly been dominated by the State of India. With the Electricity Supply Act of 1948, smaller utilities were introduced, named as State Electricity Boards (SEB). Due to the inefficient role of the SEBs, which had financial losses up to 1.3% of India's GDP, independent regulators were empowered across the country. States were given the power to pursue their own reform plans. With the introduction of these independent regulators in 1998, independent electricity regulatory commission at the level of each state have the duty of setting retail electricity tariffs and approving tariffs between Independent Power Producers (IPP) and the SEBs.

The new market structure, enables distribution utilities with ways of optimising their power purchase portfolios and reduce power purchase costs, which constitute almost 80% of the power tariff of the ultimate consumer.

Also, with the integration of the Southern Region, the grid is fully integrated as of January 2014. To be able to reliably operate this power system, a strong primary, secondary and tertiary control of frequency is required, as well as maintaining the inter-state line flows at scheduled levels. Some huge variable RE based generators cause disturbance in the grid as well. All of this requires developing an ancillary services market that will facilitate procurement of real time active and reactive power to operate the system reliably [11].

For efficient operation of the electricity market, allocation of limited transmission resources is critical. Financial Transmission Rights (FTRs) have been identified as the solution for a fair transmission allocation of transmission right between consumers [11].

### 2.2.2 Challenges to be faced

India's energy sector is unable to provide a safe supply of energy. There are six main challenges that must be addressed to stablish a well-functioning and financially-viable energy market in India [12]:

- Core capacities of the players of India's energy sector must be improved. These need to be commercially viable and have access to financial resources.
- Pricing mechanisms must ensure commercial viability and send proper signals to the market. Currently, the prices are set by the government, but sector regulators should be able to act independently from political influence. Price mechanisms should reflect realistic opportunity costs.
- The country needs significant investment to meet its everyday growing energy demand and provide access to all the population. This investment should be in green technologies that help to India's sustainable energy future.
- An increase in effective implementation of energy policies is needed to assure energy project are completed on time.
- A truly integrated and consistent energy policy is crucial to make sure India's energy sector move on the right direction and investment in ensured.
- Strong political will is essential to face the challenges in the energy sector.

Over the last two decades, the power sector has obtained a greater degree of liberalisation, which has allowed private investment along generation, transmission and distribution.

### 2.2.3 Energy policy framework

The increasing energy demand together with the concern for environmental and economic issues require an effective and thorough energy policy in India. There are three main energy policy objectives pursued by India: energy access, energy security and mitigation of climate change.

#### 2.2.3.1 Energy access

Almost 25% of the population lacks access to electricity and the Indian government identified that economic growth is being hindered by this energy poverty. Therefore, providing proper energy access to the entire population has been a main objective of the policy makers. An example of the efforts made by the government to expand access to electricity is the rural electrification scheme.

#### 2.2.3.2 Energy security

As defined by [13], “we are energy secure when we can supply lifeline energy to all our citizens irrespective of their ability to pay for it as well as meet their effective demand for safe and convenient energy to satisfy their various needs at competitive prices, at all times and with a prescribed confidence level considering shocks and disruptions that can be reasonably expected”. Therefore, India is concerned about the sudden increases in global energy prices and possible disruption.

#### 2.2.3.3 Climate change

India is engaged in reducing carbon emissions and avoiding environmental degradation. As a result of this engagement, the National Action Plan on Climate Change was announced in 2008 and the country set a goal to reduce emissions per unit of GDP by 20% to 25% below 2005 levels by 2020.

### 2.2.4 Key energy policies

#### 2.2.4.1 Electricity Act 2003

This act set a policy framework for generation, transmission, distribution, trading and consumption of electricity with market-based mechanisms as a foundation [14]. It helped promoting competition in the Indian power market, which is a result of the positive regulatory moves to create a vibrant electricity market that brings new products and solutions to benefit consumers, suppliers and the whole energy sector [11]. The EA also stated the preparation of two key policies:

- The National Electricity Policy 2005, which provided initiatives and programmes to execute the mandates of the EA 2003.

- The National Tariff Policy 2006, with the objective of strengthen the financial viability of the sector and to attract new investors.

#### 2.2.4.2 Rural Electrification Policy 2006

The objective of this policy was to ensure access to electricity to all households as well as reliable power supplies at reasonable rates [15]. Notwithstanding, it does not guarantee a reliable and daylong supply due to the uncontrolled nation-wide power shortage [12].

#### 2.2.4.3 Integrated Energy Policy 2008

The Integrated Energy Policy (IEP) was prepared to "be linked with sustainable development that covers all sources of energy and addresses all aspects of energy use and supply including energy security, access and availability, affordability and pricing, as well as efficiency and environmental concerns" [13]. One of its main features is the focus on allowing the transition to a market economy where both private and public companies compete on fair footing. Likewise, sets importance on having transparent and targeted subsidies and proper energy price signals sent to producers and consumers.

#### 2.2.4.4 National Action Plan on Climate Change

The National Action Plan on Climate Change (NAPCC) was released to achieve "a sustainable development path that simultaneously advances economic and environmental objectives" [16]. An important concept shown in the NAPCC is the per-capita carbon emission, stating that each citizen in the world has "an equal entitlement" to the global entitlement and committing that India's per-capita emission will not exceed the level of developed countries at any point [17].

## 2.3 Problems and integration

### 2.3.1 Power system issues and losses in transmission and distribution

India's power sector has always been constrained at the transmission level. Now that renewable capacities are being expanded, the need of a improved power system that does not hinder the evacuation of power to regional and national grid.

The main issue relies on the fact that while generation has grown around 50%, transmission capacity has only increased 30%, which explains why the energy demand cannot be met [18]. This implies a shortage in energy as well as a lack in energy access.

This shortage of capacity is aggravated by the transmission and distribution losses that have been estimated at 23%. Even though, in some states, these losses can go up to 50% [18]. T&D losses are divided in two groups: technical and commercial.

- Technical losses refer to the energy dissipated in the conductors and transformation equipment [19]. The main T&D losses are shown in Table 2.1.

**Table 2.1. T&D losses in various elements** [19]

| | **Power losses (%)** | |
|---|---|---|
| **System element** | **Maximum** | **Minimum** |
| Step-up transformers and transmission system | 0.5 | 1 |
| Transformation to intermediate voltage level | 1.5 | 3.0 |
| Sub-transmission system and step-down to distribution voltage level | 2.0 | 4.5 |
| Distribution lines and service connections | 3.0 | 7.0 |

  The following are the main reasons for technical losses in India:

  - Small investment on T&D
  - Too many stage transformations
  - Inadequate load management
  - Improper reactive compensation
  - Low quality of equipment used in rural areas for pumping, and air-conditioning and industrial loads in urban areas

- Commercial losses are mainly caused by pilferage, theft as well as by defective meters and erroneous meter reading [19].

### 2.3.2 Integration of renewable sources

To accommodate the growth of renewable generation, the government has planned a transmission network that is characterised by fluctuating generation and unpredictability. This project, named as “Green energy Corridor”, aims to synchronise electricity production from renewable energy sources with conventional generation systems [20].

The main issue within the existing power grid in India is voltage fluctuation, since conventional grid are not able of correctly integrating the renewable energy due to its varying voltage and fluctuation. Therefore, a more dynamic system should be sought. For this, radical changes in terms of infrastructure are needed. India’s power system is designed round controllable conventional sources of energy generation, limiting operational flexibility. The intermittent generation of renewable sources needs of changes like separate connectivity standards, dedicated teams in the existing load dispatch centres (LDCs) to manage generation and dispatch, promotion of peak and ancillary generation sources, and suitable safeguards such as frequency controllers, reactive power compensators, harmonic protectors, and over current relays. Storage systems and smarts grids will also be beneficial in terms of increasing flexibility.

Regarding the lack of capacity, the Central Electricity Authority (CEA) is planning an investment of 35bn $ to increase grid capacity through 90,000 circuit kilometres [18].

A well-coordinated generation planning and sophisticated forecasting tools and system operation techniques will allow the country to handle the variability of generation techniques.  Traditional grids cannot forecast and bear the fluctuating load brought by renewable sources, which can cause load imbalance and grid instability.

## 2.4 Stochastic cost models

Up to now, the great majority of the developed techno-economic models for renewable energies have been based in deterministic data [21]. While being correct, these evaluations are not exhaustive due to the stochasticity of some parameters of importance, which brings uncertainty to the studies. This is why lately, some researchers are working in the probabilistic regime, using probabilistic distributions instead of deterministic data [21] to foresight uncertainties in the data. Another type of model used for considering the uncertainty of the parameters is the fuzzy logic, where input parameters are expressed as fuzzy sets. Each of the fuzzy sets is described with a membership function that expresses the degree of truth.

The most used method to then analyse the stochastic data is the Monte Carlo method, which can be applied to problems in many areas such as engineering, medicine or finance [22]. A clear example of this is [23], where the impact of increasing of penetration of low carbon emission generation technologies on the price of electricity is analysed. For this work, a stochastic model has been developed, where the inputs are probability distributions for the hourly prices of electricity in different case scenarios. The tool used to this study is the @Risk software, which is an extra capability of Microsoft Excel.

# 3 METHODOLOGY

## 3.1 Problem formulation and methodology

As one of the main objectives of the energy policies in India is to fight against climate change, which includes increasing the percentage of renewables, this thesis provides and presents an energy mix where clean energy generation technologies have a higher penetration and electricity prices are still acceptable, for the population to be able to pay for it and grant energy security and access to the population. To do this prediction, as mentioned in Section 2, a stochastic approach will be used.

### 3.1.1 Monte Carlo simulations

Monte Carlo is a statistical sampling technique that uses random components as input variables subject to uncertainties and performs several iterations, to then present results in the form of probabilities [24]. This technique is used as a way of understanding the impact of risk and uncertainty in areas such as finance, costing, engineering, etc.

There are several advantages of using this method [25]:

- It allows model correlation between different variables
- The mathematics involved are relatively simple
- Several commercial software is available
- Changes and tests can be done quickly and simply
- Results are given in terms of probability distribution functions

### 3.1.2 Electricity price predictions

There are different techniques to predict electricity prices that have been widely used. For instance, [26] uses GARCH (General Autoregressive Conditional Heteroscedasticity) model to predict day-ahead market electricity prices. Another example is [27], which uses a combination of GARCH and ARMA (Autoregressive Moving Average Model) to forecast short-term electricity prices. These have proven to be effective methods, but as mentioned, are unable to do predictions for the long-term. As the aim of this work is to predict electricity prices for the long-term, a new method will be used, which is explained below.

So as to predict the prices for different energy mixes in the future in India, different case studies will be analysed. Each of the scenarios will have a different energy mix according to predictions made by organisations or just more optimistic predictions where there is a greater percentage of renewables. The electricity prices for these scenarios will be estimated as the current electricity prices for countries which have the same energy mix as the cases predicted for India. This implies assumptions and simplifications like fuel prices being the same, power plants having similar construction and O&M costs, transmission and distribution systems being similar and lastly, regulations being much the same for both cases.

### 3.1.3 Probability distributions

In order to find the energy mix that will provide cheaper electricity prices with a higher penetration of renewable energies, three scenarios will be analysed, from which results and conclusions will be obtained.

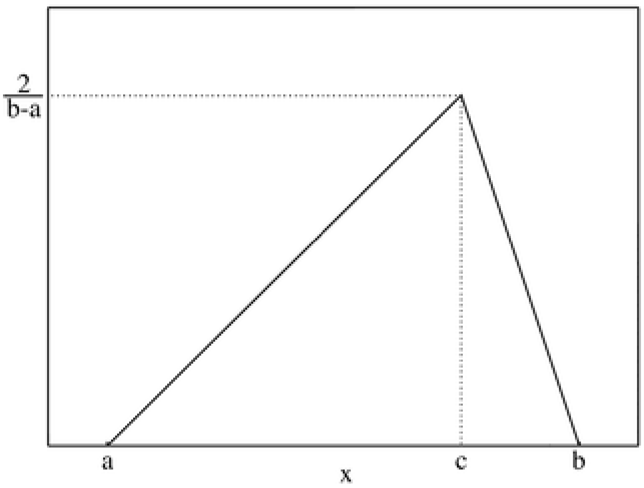


**Figure 3.1. Triangular probability distribution**

To do this analysis *@Risk* software [28] is used, which works an extension of *Excel* to perform Monte Carlo simulations. For each of the scenarios, hourly electricity prices for a day will be introduced. In total, there will be 24 input parameters, which correspond to the electricity price of each hour of the day. To account for the uncertainties and stochasticity of the electricity prices in a day, the data will be introduced in form of probability distributions. In this case, and based on [23], the probability distribution that best fits the electricity prices is a triangular distribution, which is shown in Figure 3.1. Triangular distributions are defined with three parameters: *a* and *b*, which are the lower and upper limit respectively, and *c*, which is the value with higher probability of occurrence.

The procedure followed to fit the existing data to a triangular distribution will be the following: parameter *a* will equal the minimum value of all the data and same applies for *b*, but it will equal to the maximum. Parameter *c* will be the value which has the highest probability of occurrence. To see which value fulfils this characteristic, the standard deviation for all the data for an hour is calculated, and then the absolute value of the difference between the actual value and the standard deviation will be performed. The value which meets the requirement of having this minimum absolute value will be *c* for that hour, as it will be the value which deviates less and will have a higher possibility of happening. This requirement is expressed in Equation 1.

$$\min\left|X - \sigma\right|$$ **Equation 1**

*@Risk* uses commands to define the probability distributions. In this case, as the one that will be used is a triangular distribution, the command to describe it will be Equation 2:

RiskTriang(*a*;*c*;*b*) **Equation 2**

In each of the cases, for every hour five values will be calculated: minimum value, 5% percentile, mean value, 95% percentile and maximum value, as shown in Table 3.1. All these will show in which range of values the electricity prices could fall.

**Table 3.1 Hourly electricity prices distributions and parameters**

| hour | PRICE DISTRIBUTION | min | per 5% | mean | per 95% | max |
|---|---|---|---|---|---|---|
| 1 | **0** | 0 | 0 | 0 | 0 | 0 |
| 2 | **0** | 0 | 0 | 0 | 0 | 0 |
| 3 | **0** | 0 | 0 | 0 | . | 0 |
| … | **…** | … | … | … | … | … |
| 23 | **0** | 0 | 0 | 0 | 0 | 0 |
| 24 | **0** | 0 | 0 | 0 | 0 | 0 |
| *Average* | ***0*** | *0* | *0* | *0* | *0* | *0* |

### 3.1.4 Statistical analysis

Together with the Monte Carlo stochastic analysis, a statistical analysis will be performed to analyse the volatility of the data. This will also be used as a criterion to evaluate the predictions made, since a high rate of variability of the performed data will mean the prediction is not accurate enough.

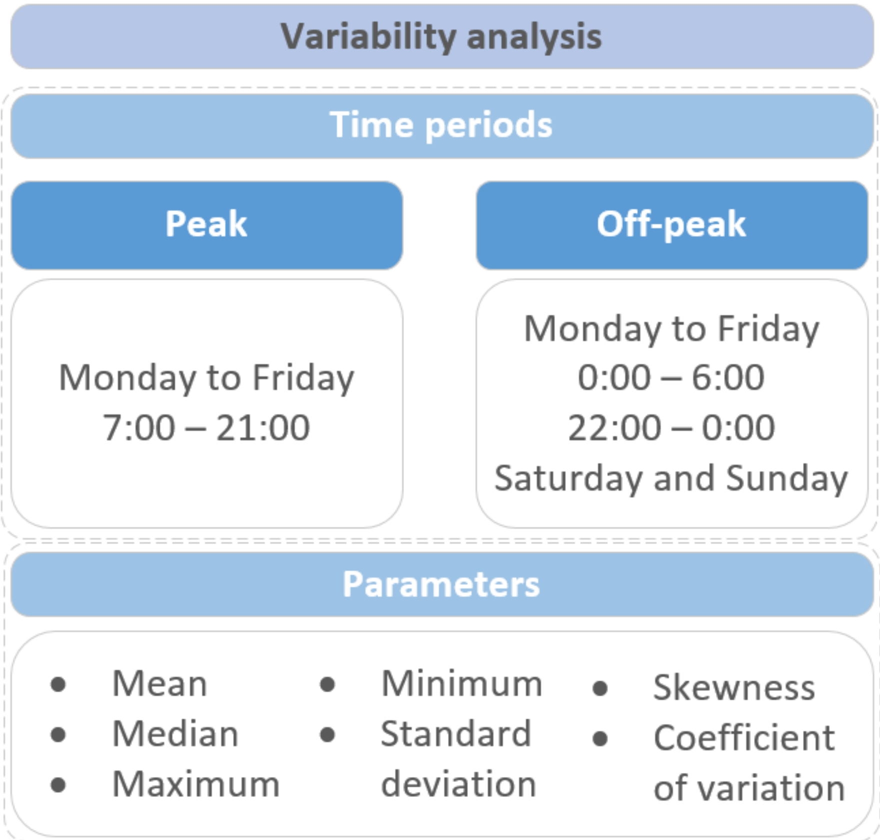


**Figure 3.2. Variability analysis methodology**

To carry out this analysis, as done in [29], a summary of the descriptive statistics of the daily electricity prices will be presented. In order to highlight the difference in electricity prices between peak and off-peak hours, as shown in Figure 3.2, two separate intervals are defined [29]:

- Peak period: 7 to 21 from Monday to Friday
- Off-peak period: remaining Monday to Friday hours along with Saturday and Sunday

This descriptive statistical analysis is done for the three scenarios and the calculated parameters are: mean, median, maximum and minimum values, standard deviation, skewness, kurtosis and coefficient of variation. Skewness measures the symmetry of the data set [30]. The coefficient of variation measures the variability of a data set, eliminating the measurement unit of the standard deviation by dividing it by the mean and it is highly used to analyse variability of data [31].

## 3.2 Scenarios

In this section, the previously mentioned scenarios will be explained, which are summarised in **¡Error! No se encuentra el origen de la referencia.**Figure 3.3.

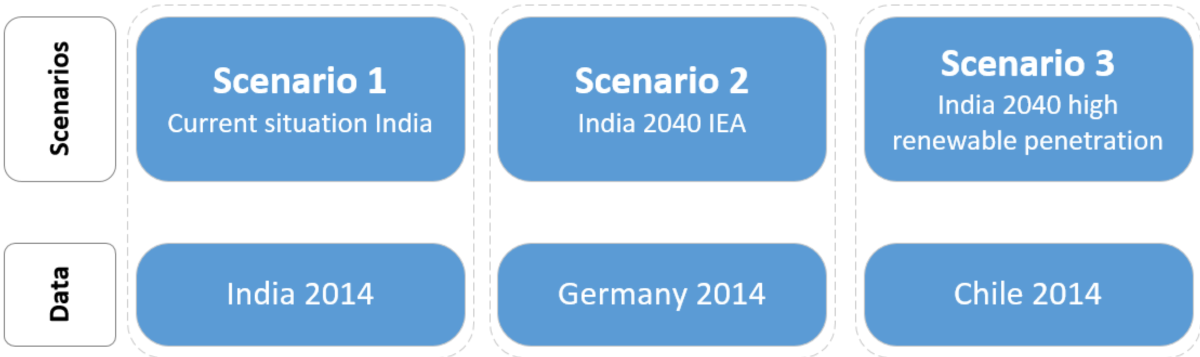


**Figure 3.3. Scenarios**

### 3.2.1 Scenario 1: Current situation in India

The scenario will correspond to the current situation in India, more specifically, to the year 2014, where the energy mix is the one showed in Table 3.2.

**Table 3.2. Energy mix in India in 2014** [1]

| **Energy mix India 2014** | |
|---|---|
| **Coal** | 72,00% |
| **Renewables** | 15,00% |
| **Gas fired** | 8,00% |
| **Nuclear** | 3,00% |
| **Liquid fired** | 2,00% |

It can clearly be seen that, as mentioned in the previous section, India mainly runs in coal to generate electricity. The data regarding the electricity prices have been obtained from [32], where the hourly electricity prices for an average week are shown in $/MWh.

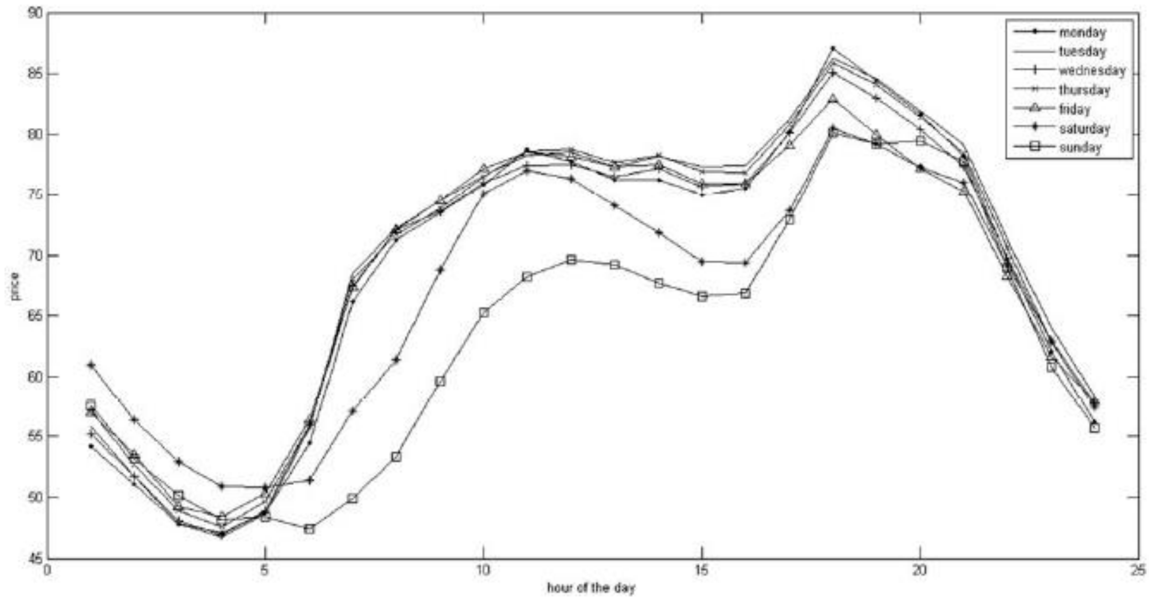


**Figure 3.4. Hourly electricity prices ($/MWh) for an average week in India** [32]

### 3.2.2 Scenario 2: India 2040 IEA

The second scenario will correspond to a replacement of 21% of coal-based electricity generation with low-carbon energy generation technologies (this encompasses renewable energies and nuclear). The data taken for this scenario corresponds to a country which currently has the energy mix predicted for India by the IEA (International Energy Agency) for 2040, which is shown in Table 3.3.

**Table 3.3. Energy mix for India 2040 predicted by IEA** [1]

| Energy mix India 2040 (IEA) | |
|---|---|
| **Coal** | 55,00% |
| **Renewables** | 28,00% |
| **Nuclear** | 9,00% |
| **Gas** | 7,00% |
| **Liquid fired** | 1,00% |

The country whose current energy mix is the most similar to this, is the one of Germany, which main source of electricity is coal but has a relatively high percentage of renewables. The energy mix for Germany in 2014 is obtained from [33] and is depicted in Table 3.4.

**Table 3.4. Energy mix in Germany in 2014** [33]

| Energy mix Germany 2014 | |
|---|---|
| **Coal** | 45,30% |
| **Nuclear** | 16,03% |
| **Gas** | 10,36% |
| **Oil** | 1.55% |
| Wind | 10,12% |
| Biomass and Waste | 7,73% |
| Solar + Tidal | 5,92% |
| Hydro | 2,99% |
| **Renewables** | 26,76% |

Therefore, comparing with the current situation, there will be a 27% substitution of coal with low-carbon technologies (mainly renewable energies, but there will also be a significant increase in the penetration of nuclear power. The electricity prices to be used for this case are obtained from [34], which shows the hourly electricity prices for Germany.

### 3.2.3 Scenario 3: India 2040 high renewable penetration

The third and last scenario corresponds to a more optimistic approach, where there will be a higher penetration of low-carbon energy technologies than in the one predicted by the IEA. A suitable country that currently has the same energy mix as this case is Chile, where coal is the main source but renewable sources have a quite large penetration percentage. The Chilean energy mix for 2014 is presented in Table 3.5.

**Table 3.5. Energy mix in Chile in 2014**

| **Energy mix Chile 2014** | |
|---|---|
| **Coal** | 33,49% |
| **Gas** | 14,59% |
| **Oil** | 8,11% |
| Hydro | 33,15% |
| Biomass and Waste | 9,91% |
| Wind | 0,75% |
| **Renewables** | 43,81% |

For this optimistic case there will be a 39% of coal substituted by low-carbon technologies, which is certainly a very optimistic prediction. The feasibility of this prediction will be analysed in the results section. The electricity prices for the Chilean case will be obtained from [35], which is Centre for Economic Load Dispatch of Northern Interconnected System of Chile. CDEC-SIC (Centro de Despacho Económico de Carga del Sistema Interconectado Central) shows the hourly electricity prices (*Costo Marginal CMG*) in $/MWh. As told by the CDEC-SIC, the information was taken for the area of Quilota, which is the most representative area of the country. Other areas that could be used and that are representative as well are Diego de Almagro, Charrúa and Puerto Montt.

# 4 RESULTS AND DICUSSION

## 4.1 Simulation results

As mentioned in Section 3, Monte Carlo simulations are used to model the electricity prices for each of the scenarios. Using *@Risk*, these simulations are performed setting the number of iterations to 10,000 to make sure the results are consistent and significant.

### 4.1.1 Current situation India

First of all, the parameters for the triangular distribution must be obtained to include them in the simulations. The previously mentioned method to fit the data to a triangular distribution yields the parameters shown in Table 4.1.

**Table 4.1. Parameters for the triangular distribution for case 1**

| Hour | a | c | b |
|---|---|---|---|
| 1 | 54,00 | 54,00 | 61,00 |
| 2 | 51,00 | 51,00 | 56,00 |
| 3 | 47,00 | 47,00 | 53,50 |
| 4 | 46,00 | 46,00 | 51,00 |
| 5 | 48,50 | 48,50 | 51,00 |
| 6 | 47,50 | 47,50 | 56,00 |
| 7 | 50,00 | 50,00 | 68,00 |
| 8 | 53,00 | 53,00 | 72,50 |
| 9 | 59,50 | 59,50 | 74,50 |
| 10 | 65,00 | 65,00 | 77,00 |
| 11 | 68,00 | 68,00 | 80,00 |
| 12 | 70,00 | 70,00 | 79,00 |
| 13 | 69,00 | 69,00 | 78,00 |
| 14 | 67,50 | 67,50 | 78,50 |
| 15 | 66,00 | 66,00 | 77,50 |
| 16 | 66,50 | 66,50 | 77,50 |
| 17 | 73,00 | 73,00 | 81,50 |
| 18 | 80,00 | 80,00 | 87,00 |
| 19 | 79,00 | 79,00 | 84,50 |
| 20 | 72,00 | 72,00 | 82,00 |
| 21 | 75,00 | 75,00 | 79,50 |
| 22 | 68,00 | 68,00 | 71,00 |
| 23 | 61,00 | 61,00 | 64,00 |
| 24 | 55,50 | 55,50 | 58,00 |

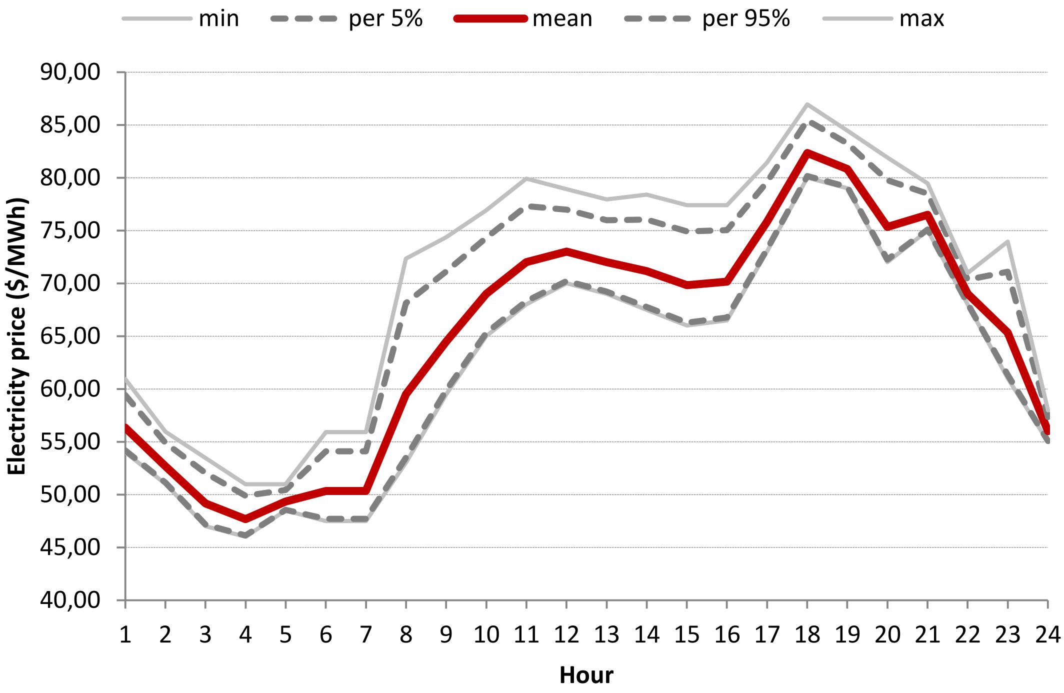


**Figure 4.1. Results of simulations for Scenario 1**

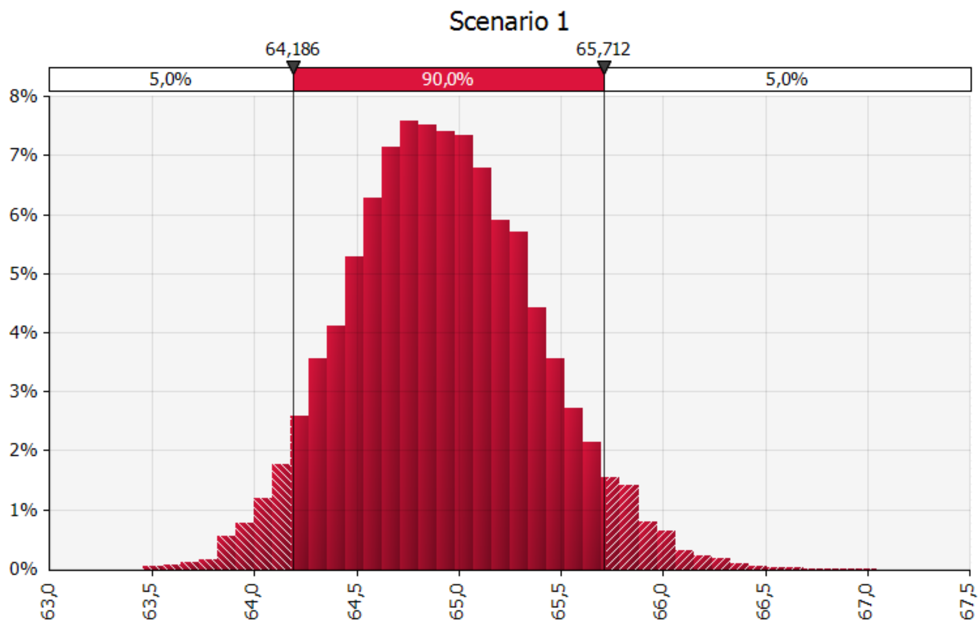


**Figure 4.2. Average price distribution for Scenario 1**

For the first scenario, which corresponds to the actual situation in India, it can be appreciated that the electricity prices range from around 45$/MWh to a maximum value of over 85$/MWh. As shown in Figure 4.2, the vast majority of the average price ranges between 64.19$/MWh and 65.71$/MWh.

### 4.1.2 India 2040 IEA

Following the same procedure as in the previous case, the parameters for the triangular distribution that fit the date are calculated. These are shown in Table 4.2.

**Table 4.2. Parameters for the triangular distribution for case 2**

| Hour | a | c | b |
|---|---|---|---|
| 1 | 16,65 | 16,65 | 40,44 |
| 2 | 12,97 | 12,97 | 40,46 |
| 3 | 12,74 | 12,74 | 41,24 |
| 4 | 17,02 | 17,02 | 41,44 |
| 5 | 16,33 | 16,33 | 56,33 |
| 6 | 16,37 | 16,37 | 80,16 |
| 7 | 28,69 | 28,69 | 81,84 |
| 8 | 33,31 | 33,31 | 86,49 |
| 9 | 33,88 | 33,88 | 79,29 |
| 10 | 35,15 | 35,15 | 79,21 |
| 11 | 32,51 | 32,51 | 68,81 |
| 12 | 28,69 | 28,69 | 65,92 |
| 13 | 19,51 | 19,51 | 67,50 |
| 14 | 21,58 | 21,58 | 67,50 |
| 15 | 29,90 | 29,90 | 67,03 |
| 16 | 32,57 | 32,57 | 75,08 |
| 17 | 36,60 | 36,60 | 103,90 |
| 18 | 40,51 | 40,51 | 76,48 |
| 19 | 40,08 | 40,08 | 65,00 |
| 20 | 38,53 | 38,53 | 52,70 |
| 21 | 37,90 | 37,90 | 48,58 |
| 22 | 33,85 | 33,85 | 43,39 |
| 23 | 32,15 | 32,15 | 43,45 |
| 24 | 27,13 | 27,13 | 42,02 |

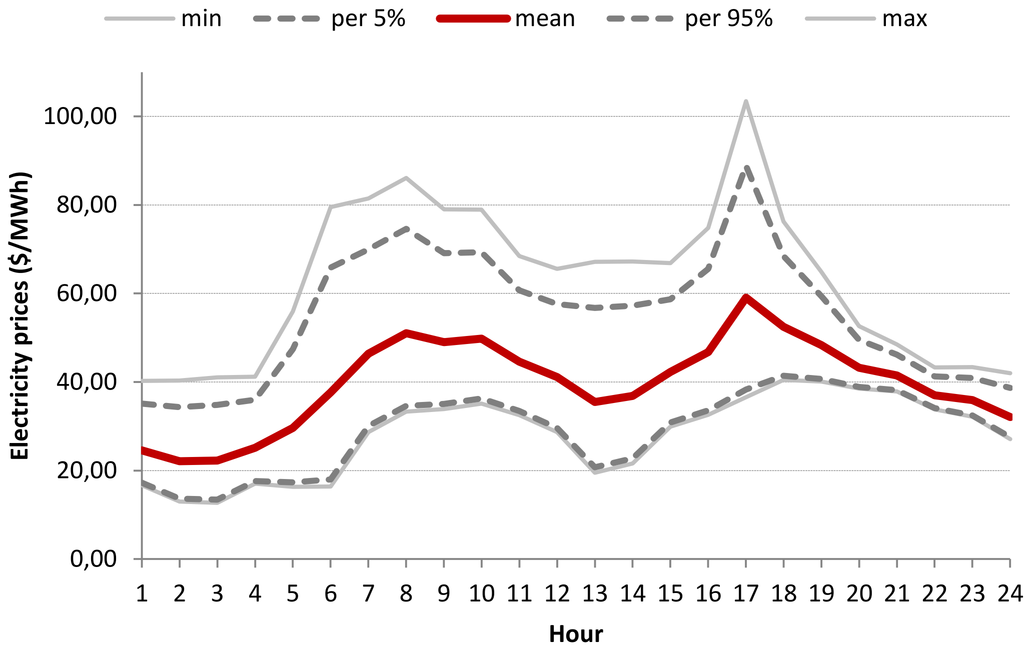


**Figure 4.3. Results of simulations for Scenario 2**

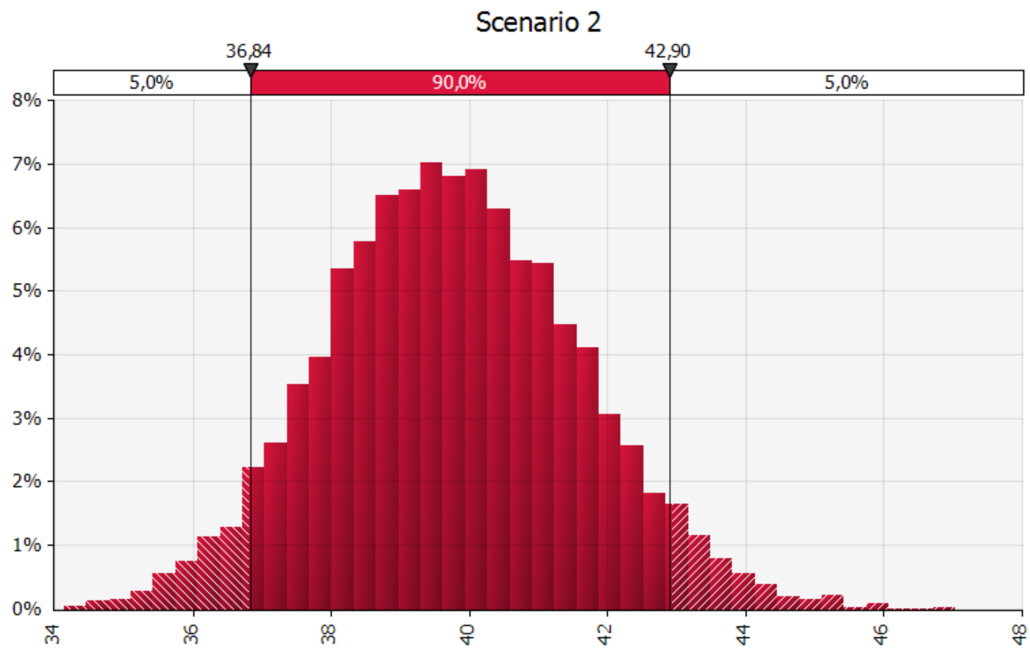


**Figure 4.4. Average price distribution for Scenario 2**

In the second scenario electricity prices are lower although variability is greater, as can be appreciated in the maximum and minimum plot lines. Also, as shown in Figure 4.4, most of the prices are in the interval of 36.84$/MWh and 42.90$/MWh.

### 4.1.3 India 2040 high renewable penetration

Lastly, and as in the previous cases, the data is fitted to triangular distribution. Table 4.3 depicts the parameters of the triangular distributions for this last case.

**Table 4.3. Parameters for the triangular distribution for case 3**

| Hour | a | c | b |
|---|---|---|---|
| 1 | 14,90 | 58,20 | 257,50 |
| 2 | 4,80 | 54,20 | 256,70 |
| 3 | 4,80 | 52,10 | 252,00 |
| 4 | 2,10 | 48,40 | 252,00 |
| 5 | 0,10 | 47,40 | 252,00 |
| 6 | 0,10 | 48,70 | 252,00 |
| 7 | 0,10 | 57,30 | 261,20 |
| 8 | 0,00 | 62,00 | 264,30 |
| 9 | 12,50 | 63,30 | 274,00 |
| 10 | 25,50 | 61,60 | 279,80 |
| 11 | 37,90 | 60,80 | 282,80 |
| 12 | 40,20 | 60,80 | 283,70 |
| 13 | 40,50 | 60,40 | 284,10 |
| 14 | 39,40 | 60,40 | 281,70 |
| 15 | 38,00 | 60,40 | 275,70 |
| 16 | 38,00 | 60,80 | 282,80 |
| 17 | 37,40 | 62,30 | 277,20 |
| 18 | 29,50 | 62,30 | 273,40 |
| 19 | 39,70 | 63,30 | 349,80 |
| 20 | 39,70 | 62,30 | 315,80 |
| 21 | 41,50 | 61,30 | 285,10 |
| 22 | 41,50 | 59,70 | 276,30 |
| 23 | 40,90 | 59,70 | 266,20 |
| 24 | 40,20 | 61,20 | 266,10 |

In the last scenario, electricity prices are clearly more variable, as can be seen in Figure 4.5. A further variability analysis will be explained in the next section for a better understanding. Regarding the values of the price of electricity, most of them fall in the interval between 115.8$/MWh and 151.8$/MWh.

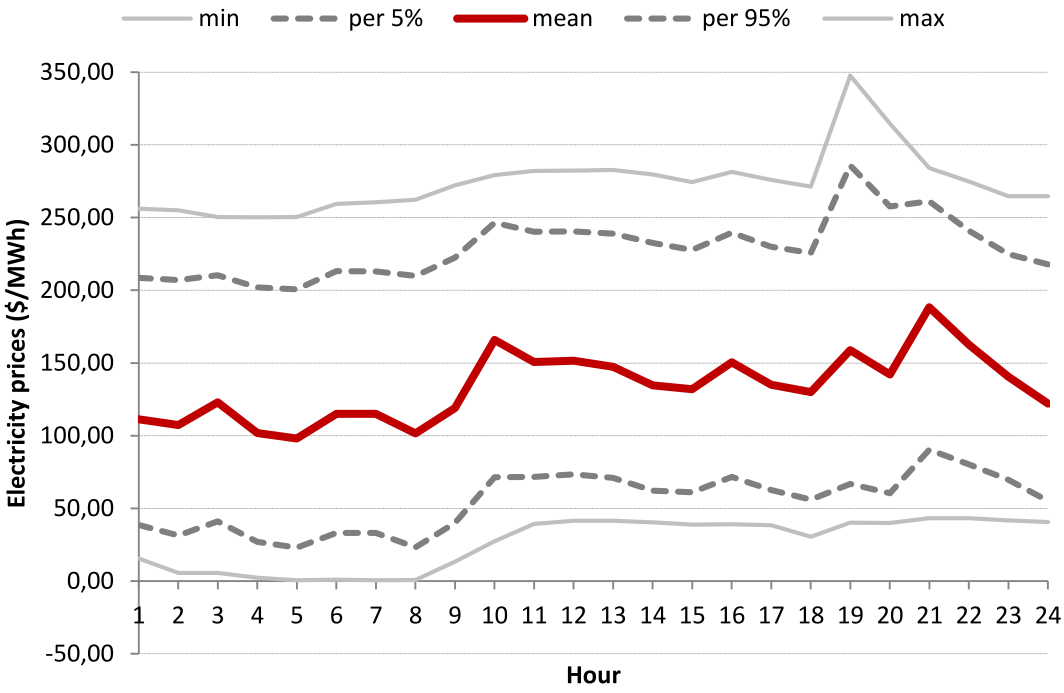


**Figure 4.5. Results of simulations for Scenario 3**

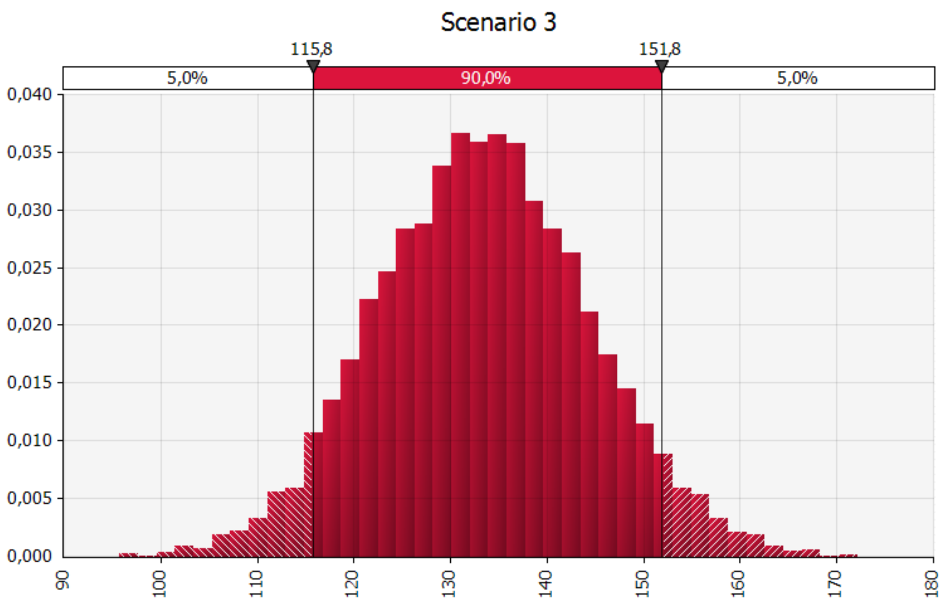


**Figure 4.6. Average price distribution for Scenario 3**

### 4.1.4 Comparison

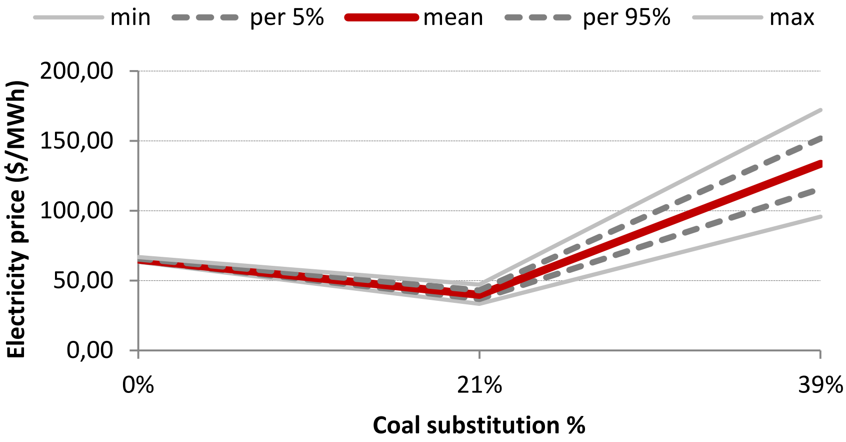


**Figure 4.7. Comparison of the three scenarios**

Figure 4.7 gathers the average electricity prices for the three scenarios. As explained before, 0% of substitution of coal for low carbon technologies corresponds to scenario 1, 21% corresponds to scenario 2 and 39% corresponds to scenario 3. It is quite clear to see that the second scenario yields a lower value of electricity prices, that is, an energy mix similar to the Germany's actual one. To complement this Monte Carlo simulations, a variability analysis will follow, so as to see which of the three cases presents a greater volatility in the prices.

## 4.2 Variability analysis

As mentioned previously, to have a more thorough understanding of the performed analysis and price modelling, a variability analysis will be shown in this section. This is done to show how variable the performed predictions are, in order to have another criterion to make a choice in terms of which of the predictions will be the one that will suit India the most. The summary statistics of peak and off-peak values are shown in Table 4.4.

**Table 4.4. Peak and off-peak variability analysis for the three scenarios**

| | India 2014 | India 2040 (IEA) | India 2040 high |
|---|---|---|---|
| **Peak** | | | |
| Mean | 77,10 | 55,12 | 147,94 |
| Median | 77,50 | 51,34 | 134,20 |
| Maximum | 87,00 | 103,90 | 284,10 |
| Minimum | 57,00 | 37,90 | 29,50 |
| Std. deviation | 4,90 | 12,09 | 60,36 |
| Skewness | 1,03 | 0,88 | 0,25 |
| Coef. of variation | 0,06 | 0,22 | 0,41 |
| **Off-peak** | | | |
| Mean | 60,19 | 38,28 | 117,42 |
| Median | 57,50 | 39,18 | 101,30 |
| Maximum | 80,00 | 80,16 | 349,80 |
| Minimum | 46,00 | 12,74 | 0,00 |
| Std. deviation | 9,98 | 10,57 | 59,75 |
| Skewness | 0,41 | 0,67 | 0,74 |
| Coef. of variation | 0,17 | 0,28 | 0,51 |

## 4.3 Results discussion

First of all, and as displayed in Figure 4.7, scenario 2 will give a lower price of electricity. This scenario corresponds to a 28% of renewables in the energy mix of India. Scenario 3 has a greater percentage of renewable energy, which India won't be able to accommodate for due to the poor power infrastructure. Chile, like India, is a country in need of a reliable supply. Developments in generation and transmission lines have not been in line with the economic growth of the country. It has heavily relied on sources like coal or oil to cope with the growing demand, without focusing on a long term strategy to improve the power system [36]. These generation technologies are costly to build and run, which causes the electricity prices to go up. Also, the particular shape of the country causes constraints in the transmission lines, making it unable to cope with all the generated electricity.

Therefore, Chile and India are quite similar in terms of the power systems infrastructure, and introducing a great percentage of renewable generation would mean the system not being able to cope with it.

To verify how good the results of the simulations are, they are fitted to a normal distribution to analyse the error made. For each of the three scenarios and using *@Risk*, the data of the results is fitted to a distribution. *@Risk* identifies the normal distribution as the most suitable one for each of the cases. Results of these fittings are shown in Figure 4.8, Figure 4.9 and Figure 4.10.

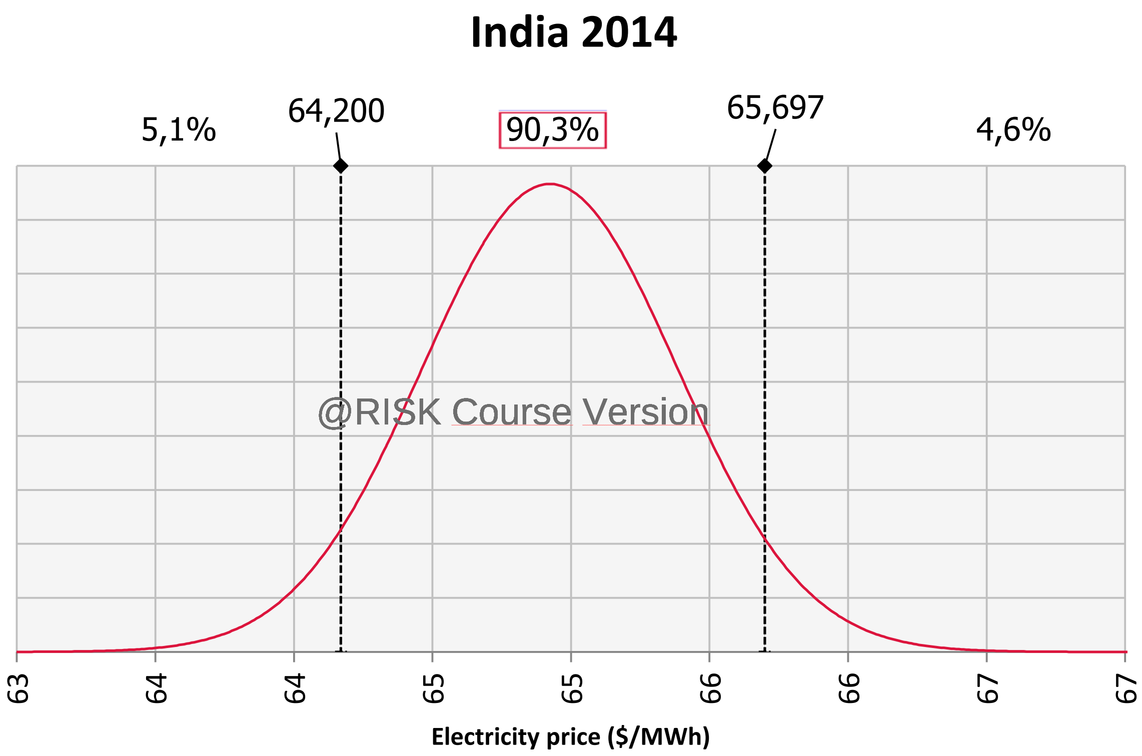


**Figure 4.8. Fitting of results of scenario 1**

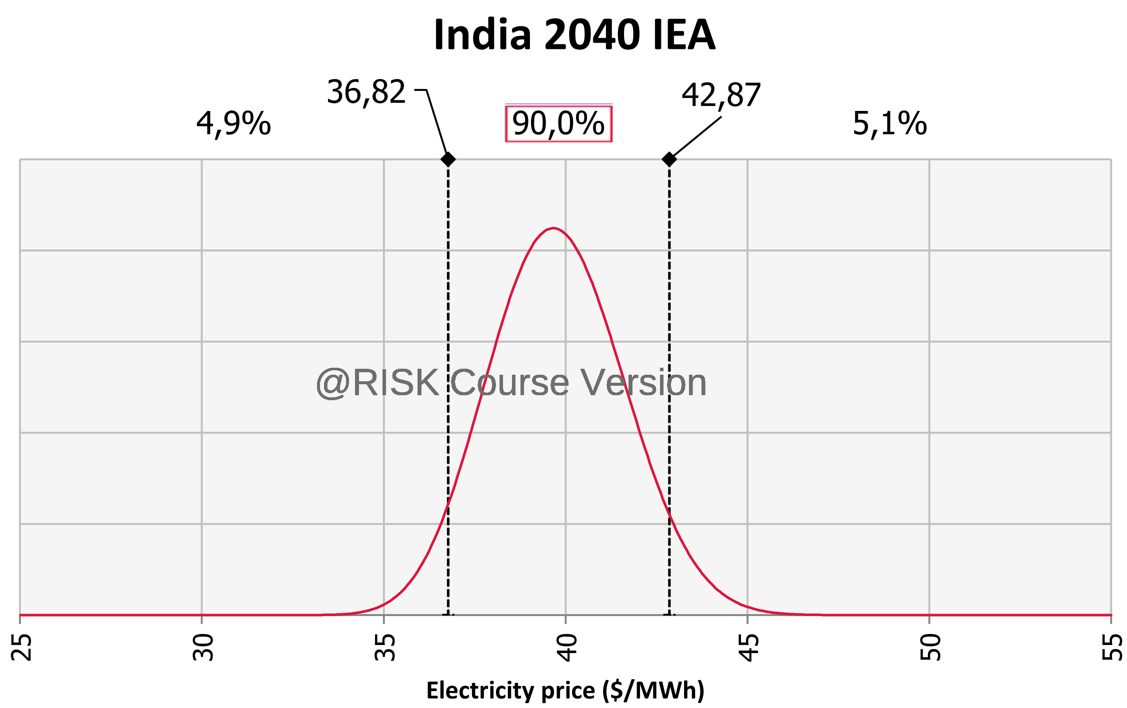


**Figure 4.9. Fitting of results of scenario 2**

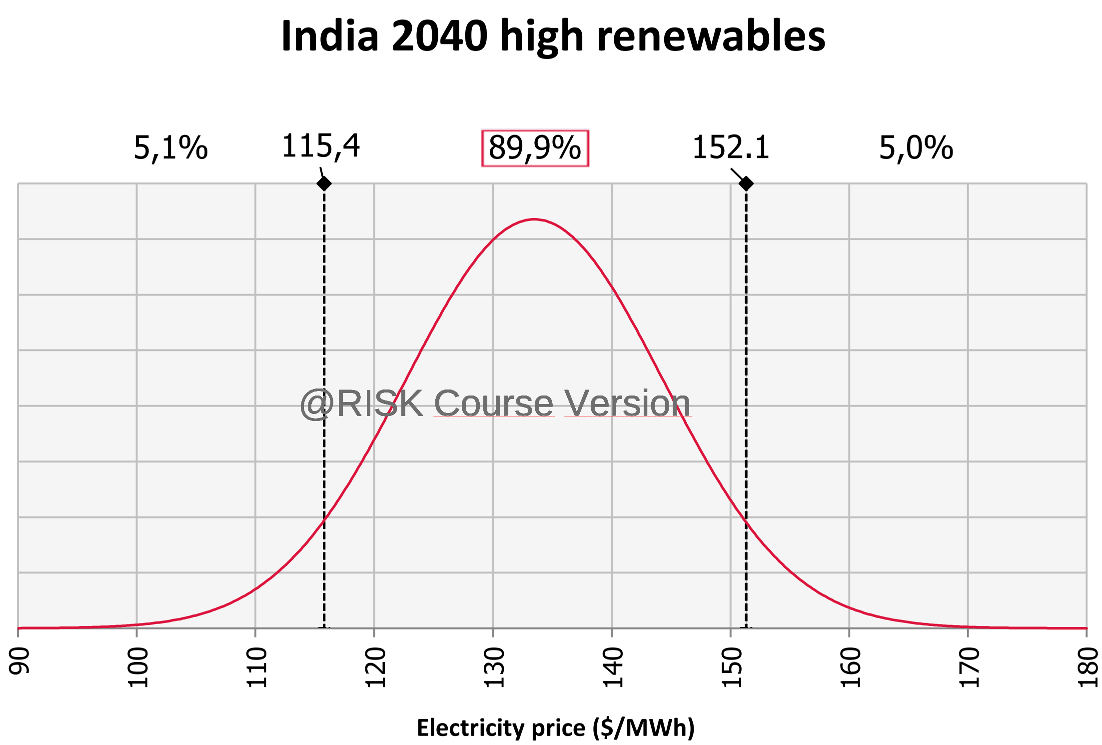


**Figure 4.10. Fitting of results of scenario 3**

As can be appreciated in the figures above, the majority of the fitted curve falls in around 90% of the most repeated values, leaving only 5% in both tails. To analyse how good the fitting is, as done in [23], the ranges where the 90% of the data fall are compared. For the first scenario 90% of the fitted data fall in the range 64.200 and 65.697 which is very similar to the one the results, which was 64.186 and 65.712. In the second scenario, the majority of the fitted data falls in the range 36.82 and 42.87 which compared to the results 36.84 and 42.90 is a quite good fitting. Finally, in scenario 3, the range of the fitted data, 115.4 and 152.1, is comparable to the one obtained in the results, 115.8 and 151.8. This means that the fitting is reasonably well done and that the results are quite significant.

Regarding the variability analysis, it is clear to see that scenario 3 would have a greater volatility in electricity prices since the coefficient of variation is higher for that case (0.41 and 0.51 compared to 0.22 and 0.28 for scenario 2). All the price series are positively skewed, indicating a greater probability of increase in prices. Also, taking into account the division between peak and off-peak intervals, the variability is greater for the latter case, since the coefficient of variation is higher.

# 5 CONCLUSSIONS AND FUTURE WORK

The main aim of this thesis was to find an energy mix for India that would have a higher percentage of renewable energies while maintaining a reasonable price in electricity. From the simulations performed, we can conclude that India cannot cope with a high percentage of substitution of coal for renewable sources, since the higher the percentage is, the higher the electricity price will be.

The main reason for this increase in the electricity price is power system infrastructure of India, which is quite poor and cannot accommodate the high percentage of renewable within the system. Losses in transmission and distribution are also a very important problem, since they can be of 50% in some states, which make the power system very inefficient [11].

Therefore, the optimal percentage of substitution of coal for low-carbon technologies will be around 21% until significant improvement on T&D infrastructure are made. This percentage would provide lower electricity prices while introducing more renewable energy sources to meet the objectives of the policies introduced by the Indian government.

To be able to accommodate a higher percentage of renewables, the system must increase its flexibility as well as its capacity. Restructuring the whole system to have a higher capacity can result costly and complex. Thus, adding flexibility to the grid by introducing storage and using smarts grids would be an ideal solution to reduce the problems in the power system. Energy storage systems would be a feasible solution to store energy when there is excessive generation and balance the excess generation to inject it to the grid when it is demanded. Likewise, smarts grids controlled by the application of extensive information and communication technologies, would provide a higher reliability and increased efficiency. Distribution should also become bi-directional so as to transfer power in reverse direction.

Finally, the variability of electricity prices should be kept within reasonable limits to ensure that one of the three objectives of the energy trilemma [13], energy access, is fulfilled and all the Indian population has access to electricity.

In terms of future work, having broader historical data of electricity prices for each of the scenarios would provide a deeper insight in price volatility, since results would offer better insights.

Also, this study has been focused in long-term modelling and prediction of electricity prices, but a short or medium-term forecast would also be convenient. For this, techniques such as GARCH or ARMA modelling can be used, a with the previous mentioned broader historical data. This analysis, together with the one presented in this report would make a complete study on the analysis of the electricity prices in India with more penetration of renewable energies.

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# APPENDICES

## Appendix A Simulation results

### A.1 Results for Scenario 1

**Table_Apx 1. Simulation results for Scenario 1**

| hour | PRICE DISTRIBUTION | min | per 5% | mean | per 95% | max |
|---|---|---|---|---|---|---|
| 1 | **59,68** | 59,68 | 59,68 | 59,68 | 59,68 | 59,68 |
| 2 | **51,55** | 51,55 | 51,55 | 51,55 | 51,55 | 51,55 |
| 3 | **48,65** | 48,65 | 48,65 | 48,65 | 48,65 | 48,65 |
| 4 | **47,54** | 47,54 | 47,54 | 47,54 | 47,54 | 47,54 |
| 5 | **49,55** | 49,55 | 49,55 | 49,55 | 49,55 | 49,55 |
| 6 | **50,49** | 50,49 | 50,49 | 50,49 | 50,49 | 50,49 |
| 7 | **48,50** | 48,50 | 48,50 | 48,50 | 48,50 | 48,50 |
| 8 | **68,49** | 68,49 | 68,49 | 68,49 | 68,49 | 68,49 |
| 9 | **64,55** | 64,55 | 64,55 | 64,55 | 64,55 | 64,55 |
| 10 | **72,33** | 72,33 | 72,33 | 72,33 | 72,33 | 72,33 |
| 11 | **72,20** | 72,20 | 72,20 | 72,20 | 72,20 | 72,20 |
| 12 | **72,47** | 72,47 | 72,47 | 72,47 | 72,47 | 72,47 |
| 13 | **69,14** | 69,14 | 69,14 | 69,14 | 69,14 | 69,14 |
| 14 | **72,11** | 72,11 | 72,11 | 72,11 | 72,11 | 72,11 |
| 15 | **71,17** | 71,17 | 71,17 | 71,17 | 71,17 | 71,17 |
| 16 | **70,67** | 70,67 | 70,67 | 70,67 | 70,67 | 70,67 |
| 17 | **78,22** | 78,22 | 78,22 | 78,22 | 78,22 | 78,22 |
| 18 | **80,11** | 80,11 | 80,11 | 80,11 | 80,11 | 80,11 |
| 19 | **80,57** | 80,57 | 80,57 | 80,57 | 80,57 | 80,57 |
| 20 | **79,16** | 79,16 | 79,16 | 79,16 | 79,16 | 79,16 |
| 21 | **76,69** | 76,69 | 76,69 | 76,69 | 76,69 | 76,69 |
| 22 | **69,19** | 69,19 | 69,19 | 69,19 | 69,19 | 69,19 |
| 23 | **62,94** | 62,94 | 62,94 | 62,94 | 62,94 | 62,94 |
| 24 | **56,10** | 56,10 | 56,10 | 56,10 | 56,10 | 56,10 |
| *Average* | ***65,50*** | 65,50 | *65,50* | *65,50* | *65,50* | *65,50* |

## A.2 Results for Scenario 2

**Table_Apx 2. Simulation results for Scenario 2**

| hour | PRICE DISTRIBUTION | min | per 5% | mean | per 95% | max |
|---|---|---|---|---|---|---|
| 1 | **28,89** | 28,89 | 28,89 | 28,89 | 28,89 | 28,89 |
| 2 | **26,18** | 26,18 | 26,18 | 26,18 | 26,18 | 26,18 |
| 3 | **14,48** | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 |
| 4 | **19,01** | 19,01 | 19,01 | 19,01 | 19,01 | 19,01 |
| 5 | **40,73** | 40,73 | 40,73 | 40,73 | 40,73 | 40,73 |
| 6 | **23,01** | 23,01 | 23,01 | 23,01 | 23,01 | 23,01 |
| 7 | **32,35** | 32,35 | 32,35 | 32,35 | 32,35 | 32,35 |
| 8 | **49,09** | 49,09 | 49,09 | 49,09 | 49,09 | 49,09 |
| 9 | **46,23** | 46,23 | 46,23 | 46,23 | 46,23 | 46,23 |
| 10 | **41,25** | 41,25 | 41,25 | 41,25 | 41,25 | 41,25 |
| 11 | **58,90** | 58,90 | 58,90 | 58,90 | 58,90 | 58,90 |
| 12 | **37,05** | 37,05 | 37,05 | 37,05 | 37,05 | 37,05 |
| 13 | **21,17** | 21,17 | 21,17 | 21,17 | 21,17 | 21,17 |
| 14 | **28,83** | 28,83 | 28,83 | 28,83 | 28,83 | 28,83 |
| 15 | **42,69** | 42,69 | 42,69 | 42,69 | 42,69 | 42,69 |
| 16 | **37,98** | 37,98 | 37,98 | 37,98 | 37,98 | 37,98 |
| 17 | **55,24** | 55,24 | 55,24 | 55,24 | 55,24 | 55,24 |
| 18 | **71,46** | 71,46 | 71,46 | 71,46 | 71,46 | 71,46 |
| 19 | **52,57** | 52,57 | 52,57 | 52,57 | 52,57 | 52,57 |
| 20 | **46,04** | 46,04 | 46,04 | 46,04 | 46,04 | 46,04 |
| 21 | **41,90** | 41,90 | 41,90 | 41,90 | 41,90 | 41,90 |
| 22 | **40,61** | 40,61 | 40,61 | 40,61 | 40,61 | 40,61 |
| 23 | **36,58** | 36,58 | 36,58 | 36,58 | 36,58 | 36,58 |
| 24 | **31,31** | 31,31 | 31,31 | 31,31 | 31,31 | 31,31 |
| *Average* | ***38,48*** | *38,48* | *38,48* | *38,48* | *38,48* | *38,48* |

## A.3 Results for Scenario 3

**Table_Apx 3. Simulation results for Scenario 3**

| hour | PRICE DISTRIBUTION | min | per 5% | mean | per 95% | max |
|---|---|---|---|---|---|---|
| 1 | **118,03** | 118,03 | 118,03 | 118,03 | 118,03 | 118,03 |
| 2 | **68,08** | 68,08 | 68,08 | 68,08 | 68,08 | 68,08 |
| 3 | **219,56** | 219,56 | 219,56 | 219,56 | 219,56 | 219,56 |
| 4 | **141,43** | 141,43 | 141,43 | 141,43 | 141,43 | 141,43 |
| 5 | **128,92** | 128,92 | 128,92 | 128,92 | 128,92 | 128,92 |
| 6 | **103,76** | 103,76 | 103,76 | 103,76 | 103,76 | 103,76 |
| 7 | **50,62** | 50,62 | 50,62 | 50,62 | 50,62 | 50,62 |
| 8 | **186,18** | 186,18 | 186,18 | 186,18 | 186,18 | 186,18 |
| 9 | **133,01** | 133,01 | 133,01 | 133,01 | 133,01 | 133,01 |
| 10 | **152,69** | 152,69 | 152,69 | 152,69 | 152,69 | 152,69 |
| 11 | **93,50** | 93,50 | 93,50 | 93,50 | 93,50 | 93,50 |
| 12 | **171,03** | 171,03 | 171,03 | 171,03 | 171,03 | 171,03 |
| 13 | **74,34** | 74,34 | 74,34 | 74,34 | 74,34 | 74,34 |
| 14 | **164,29** | 164,29 | 164,29 | 164,29 | 164,29 | 164,29 |
| 15 | **218,30** | 218,30 | 218,30 | 218,30 | 218,30 | 218,30 |
| 16 | **216,65** | 216,65 | 216,65 | 216,65 | 216,65 | 216,65 |
| 17 | **117,12** | 117,12 | 117,12 | 117,12 | 117,12 | 117,12 |
| 18 | **149,52** | 149,52 | 149,52 | 149,52 | 149,52 | 149,52 |
| 19 | **104,06** | 104,06 | 104,06 | 104,06 | 104,06 | 104,06 |
| 20 | **107,01** | 107,01 | 107,01 | 107,01 | 107,01 | 107,01 |
| 21 | **227,68** | 227,68 | 227,68 | 227,68 | 227,68 | 227,68 |
| 22 | **201,88** | 201,88 | 201,88 | 201,88 | 201,88 | 201,88 |
| 23 | **95,90** | 95,90 | 95,90 | 95,90 | 95,90 | 95,90 |
| 24 | **86,37** | 86,37 | 86,37 | 86,37 | 86,37 | 86,37 |
| *Average* | ***138,75*** | *138,75* | *138,75* | *138,75* | *138,75* | *138,75* |