

# CHAPTER- I

## INTRODUCTION

---

### 1.1 GENERAL BACKGROUND

Energy generation plays a significant role in making life simple, easy and remarkable advancement in human existence. The basic requirement of day to day activities cannot be achieved without the involvement of energy. Energy has a great contribution in the development of any country because it acts as an engine of new innovations, ideas, and investments that creates numerous opportunities and products which results in the overall growth of the country. It is normally produced from different sources of renewable and non-renewable resources. The non-renewable energy resources are broadly divided into four categories such as coal, oil, natural gas, and nuclear energy. Whereas renewable energy resources are majorly generated from solar, hydro, wind, geothermal, tidal, and biomass energy. The non-renewable energy resources can also be called as fossil fuel which needs millions of years for their formation, furthermore it is available in limited quantity. The contribution of different source of energy in the world's total primary energy consumption has been shown in Fig. 1.1. Fossil fuels are the real backbone of the energy production that contributes around 80% of the total energy production of the world (EESI 2023). By 2060, all of our fossil fuel reserves are predicted to be used up if we continue burning them at our current rate (Octopus energy 2023). Also, it is expected that the depletion of oil will be earlier than the coal and natural gas. The main obstacle with the fossil fuels are, it creates land degradation during unearthing, water pollution, emission of CO<sub>2</sub> or other toxic gasses due to

burning, global warming, and ocean acidification. There are more than 34000 mining place available around the world which covers all types of large scale, small scale, and artisanal mining locations. The satellite images of all mining locations were interpreted for land use pattern and found the total mining area of 101,583 km<sup>2</sup> that is roughly equivalent to five times the area of the country named Wales (Maus et al. 2022). The annual world CO<sub>2</sub> emission from the combustion of fossil fuel was estimated to be 300 million tonnes in the year 2022 that is approximately equivalent to the weight of the population of human being (IEA 2022). Therefore, the average increase of 1°C (1.7 °F) has been observed over the average temperature of the world since 1880. The global climatic temperature is estimated to be increased by 1.5 °C (2.7 °F) at the end of 2050, furthermore this increase in global temperature will be in the between 2-4 °C (3.6-7.2 °F) at the end of the 21<sup>st</sup> century (Collins et al. 2013).

### **1.1.1 Global Overview on Fossil Fuel**

For better visualization, the average annual per capita consumption of United States' fossil fuel having an average height of 5.6 feet has been represented in the form of a cube. It provides the average height of the cube for coal, oil (petroleum products), and natural gas are 3.9 feet, 4.9 feet, and 9.5 feet respectively (World bank 2023). The world's recoverable coal reserves are mostly concentrated in five countries (United States, Russia, Australia, China, and India) which exist of the order of 1161 billion short tonnes in the year 2021 (EIA 2022) that can be seen in Fig. 1.2(a). Whereas, the dominance of coal among the other sources in the electricity production for top fossil fuel dependent countries has been depicted in Fig. 1.2(b). In the year 2016, the annual coal demand was around 1147083 cubic feet per person. Based on the current demand and the availability of total reserves, it can be predicted that the coal has left only for 133 years for further use (Worldometer 2023<sup>1</sup>).

## World total primary energy consumption by fuel

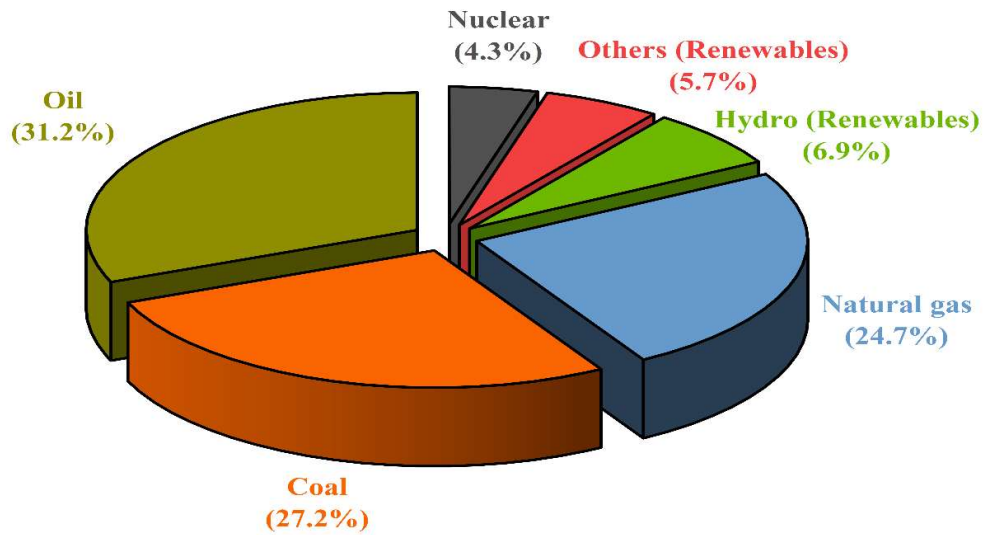
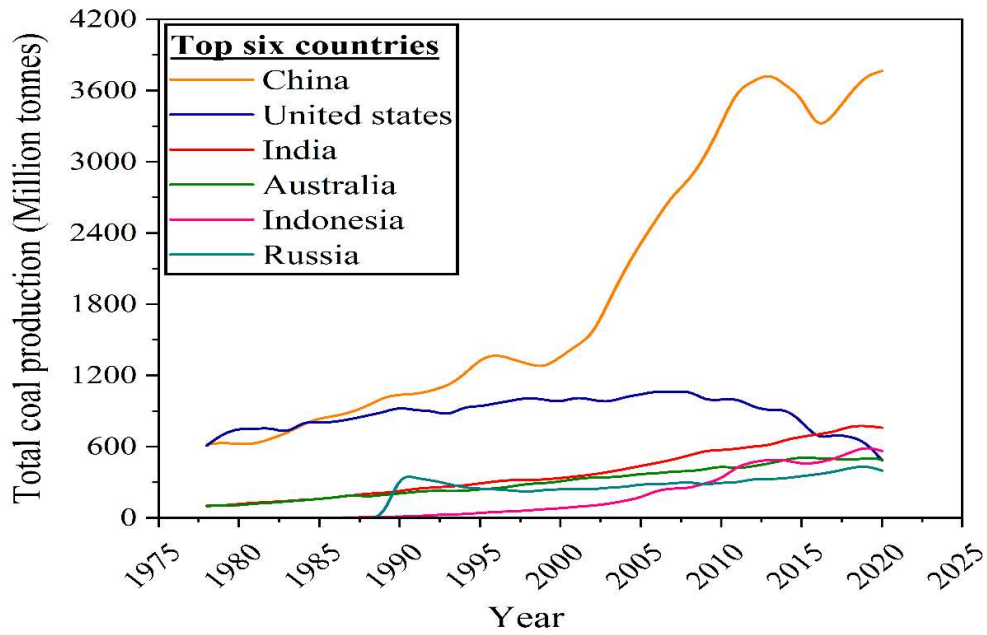
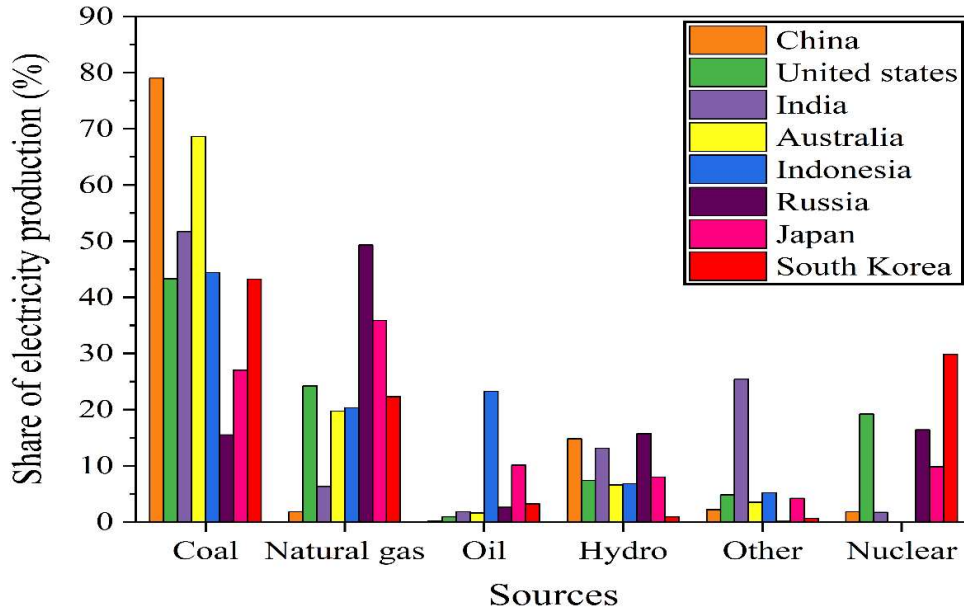


Fig. 1.1. The contribution of different source of energy in the world's total primary energy consumption. (Source: Statistics review of world energy 2021)



(a)



(b)

Fig. 1.2. Typical representation of (a) coal production growth, and (b) share of various sources in the electricity production of top fossil fuel consumer countries. (Source: World development indicators 2021)

Similarly, the world’s oil reserves are presented in the form of barrel and it is estimated that around 1.73 trillion barrels are available as total reserve. These oil reserves were significantly distributed to the countries located to the western side of India, among all the Venezuela and Saudi Arabia covers approximately 35% of the total oil reserves. After this, Canada, Iran, Russia, Kuwait, United Arab Emirates, and United States covers 50% of the total oil reserves (SRWE 2021<sup>1</sup>). The oil has frequent application in the transportation sector, heat and electricity generations. The annual consumption of oil per person in the year 2016 was found to be 800 litres (approx.) (or 80 litres per person per day) (Worldometer 2023<sup>2</sup>). Based on this demand, the estimated time required to finish the total oil reserve is 47 years. The total world’s proved natural gas reserves are found to be 6641.8 Trillion cubic feet which are abundantly available near Arab countries (SRWE 2021<sup>2</sup>). Russia has highest natural gas reserves followed

by Iran, Qatar, United States, Saudi Arabia, Turkmenistan, and United Arab Emirates have 70% of the total natural gas reserves. The world average annual consumption of natural gas is about 17527 cubic feet per person (or 48 cubic feet is required by per person per day) as per world population data of 2017 (Worldometer 2023<sup>3</sup>). According to the current consumption rate of natural gas, it will take only 52 years to complete consumption of the total world reserve. From the above discussion, this can be interpreted that the fossil fuels are non-recyclable and are available for a stipulated period of time. In the present scenario, we are highly dependent on the fossil fuel to meet our daily requirements and least dependent on the renewable energy resources. The burning of fossil fuel is responsible for the production of 75% greenhouse gases and 90% of CO<sub>2</sub> emissions. In order to avoid the harmful impact of the fossil fuels to the environment, it is significant to shift the energy production need towards sustainable energy sources. The International Renewable Energy Agency also recommended that the world's electricity generation should be maximized (about 90%) by utilizing renewable energy resources till 2050 (UN Climate action 2023). The Remap (global energy modelling) framework analyzes the emission of CO<sub>2</sub> between the year 2010-2050 which considered the efficient energy and higher contribution of the recyclable energy as two key factors. From the results, they concluded that the energy transition towards the renewable energy resources lead to the reduction of 94% of CO<sub>2</sub> emission by the year 2050 (Gielen et al. 2019).

### **1.1.2 India's Stance on Fossil Fuels**

Following China, India is the world's second-largest coal producer with projected coal reserve of 352.13 billion tonnes as of April 2021. The coal reserves are predominantly distributed in the eastern, northeastern, central, western and south-central part of India. More than 95% of the coal reserves were majorly confined in seven states having

highest reserves in Jharkhand followed by Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana, and Maharashtra. The overall coal demand was 956 million tonnes in the year 2019-20 and as per the requirement trend it is projected to achieve the demand of 1448 million tonnes by 2029-30 (Ministry of coal 2022<sup>1</sup>). The coal is broadly divided into two categories based on their quality. The lignite is the other category of the coal normally used in the electricity generation. It is the lowest grade of coal having low carbon content (60-70%) and high moisture content (30-55%). Lignite has maximum reserves in the northern (Jammu and Kashmir), western (Rajasthan and Gujrat), southern (Tamil Nadu) part of India with total reserve of 46.02 billion tonnes (Ministry of coal 2022<sup>2</sup>). Similarly, the crude oil is another source of non-renewable energy having total reserves of 603.36 million tonnes at the end of 2020 (Energy statistics 2022). The 90% of oil reserves are mostly distributed in the western offshore, eastern offshore, Gujarat, and Assam. India is at 24<sup>th</sup> position in the world in terms of geographical oil production that is why India is the second largest crude oil importer to fulfill the current demand. The natural gas is the third most popular fossil fuel those are usually available near oil reserves. Therefore, natural gas also has the same reserve location like crude oil, i.e., western offshore, eastern offshore, Assam etc. India is ranked 29<sup>th</sup> in the world for natural gas production capacity, with an estimated reserve of 1372.62 billion cubic meters (Energy statistics 2022). There are several renewable energy resources such as solar energy, wind power, small hydropower, biomass, waste to energy etc. available in India. Seeing the devastating effect of fossil fuel to climate change, the government has taken many initiatives to promote sustainable energy resources. Currently, 80% of the energy generation are through non-renewable sources and 20% through renewable sources. The estimation of central electricity authority predicts that the contribution of the energy generated from the non-renewable sources

would decrease up to 52% while the share of renewable sources would increase up to 44% by 2030 (IBEF 2023). Also, the Indian government is targeting to achieve 100% energy generation from the renewable energy resources that means net zero emissions by 2070 (IEA 2022). The summary of the above discussion is that the coal is the primary and cheapest source of energy generation as compared with the other sources because India is a top largest coal producing country. The complete elimination of coal will take another 4-5 decades from the energy sector considering the growth of renewable resources. The burning of coal results in the coal combustion residues also known as coal ash along with the harmful gases. The coal ash normally generated in millions of tonnes which again creates nuisance in the environment. Hence, it is essential to go through this problem and provide sustainable solution to reduce its impact on the environment. The detailed evaluation of coal and its ash generation has been discussed in the subsequent sections.

### **1.1.3 Coal and Its Ash Generation in India**

The share of various sources such as coal/lignite, gas, hydro, wind+solar+other renewable resources, and nuclear are 51.3%, 6.1%, 11.4%, 29.5%, and 1.7% respectively in the electricity generation (Ministry of Power 2023). In India, the coal is the cheapest source of energy due to its abundant availability. But the problem associated with Indian coal is that it has the high ash producing capability in the range between 30 to 60% and low calorific value (Asokan et al. 2005). The share of different energy sources to installed power generation capacity has been shown in Fig. 1.3. It shows past 76-years data having higher contributions from the coal than that of the other sources. But during the last 20 years, it has been seen that the renewable resources have increased while coal's share has decreased. There are 200 active thermal power stations in which the total coal consumption was 759.02 million tonnes in the year 2021-

22. If we take the average ash content of coal equals to 40% then 759.02 million tonnes of coal will convert into residue of 303.608 million tonnes. This coal combustion residue generally composed of two types of coal ash, a) fly ash, and b) bottom ash.

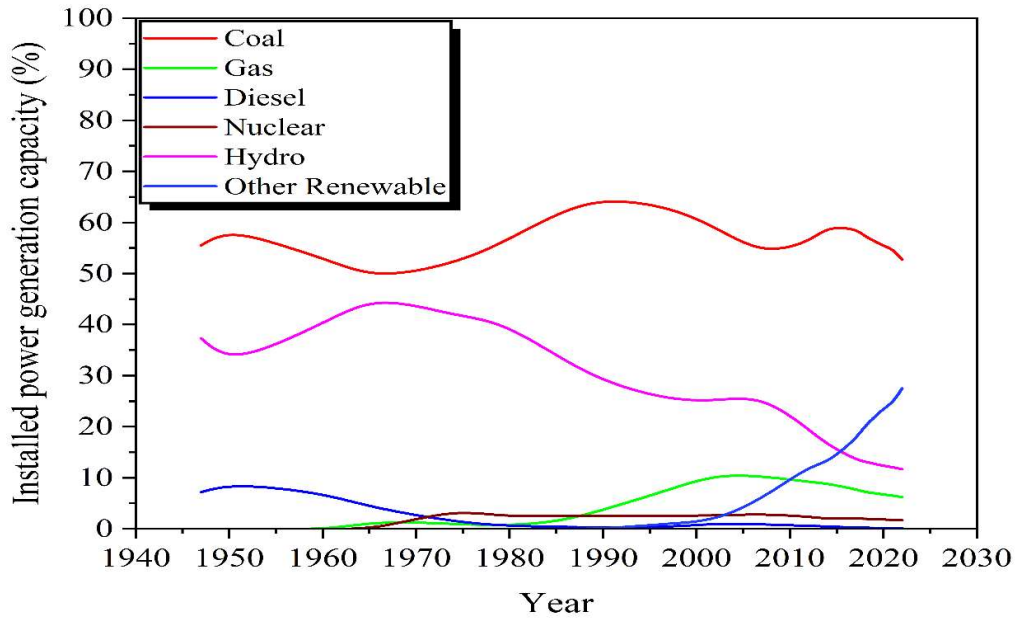


Fig. 1.3. Contribution of various sources in the installed power generation capacity in India. (Source: CAE 2020)

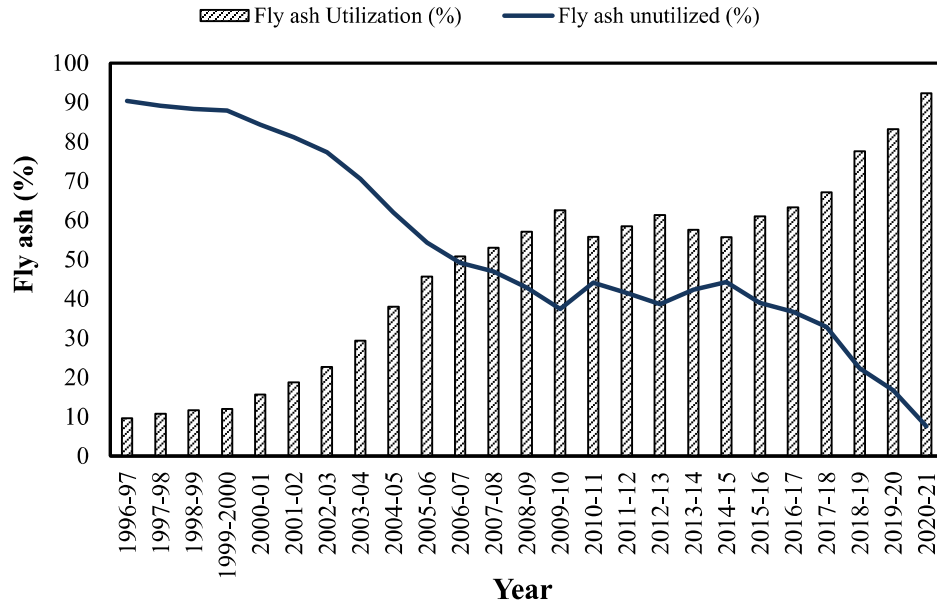


Fig. 1.4. Demonstration of fly ash utilization and non-utilization during 25-years duration. (Source: CEA 2022)

In the coal combustion residue, the fly ash has contribution of about 70-80% and the rest will be the bottom ash (Singh et al. 2012). The fly ash generated in the year 2021-22 was found to be 270.82 million tonnes (MT), and this will be projected to cross 437 MT by the year 2030. In India, the amount of fly ash produced over a period of 25-years is approximately 3335.9 million tonnes (MT), of which only 55% (1834.83 MT) have been used and the remaining 45% (1501 MT) is still in their unutilized form. Initially, the unutilized fraction was high till 2007 after that the utilized fraction starts dominating that can be seen in Fig. 1.4. Although the utilization of freshly generated coal ashes is high but the accumulated fraction of unutilized coal ash is a major point of concern. Because wet coal ash cannot be used in the place where the pozzolanic reaction or bonding properties are significantly required. The land covered by the coal ash from the conventional slurry disposal technique is around 2300 hectares for 128 MT of fly ash and that needs 1.3 billion m<sup>3</sup> of water for their disposal (Mission Energy

2020). The coal ash produced in the thermal power plants usually dumped near to the power plant in Millions of tonnes.

#### 1.1.4 Coal Ash Handling System

In thermal power plants, coal is the major source of energy which is required to produce steam. The complete step by step process of coal driven thermal power plant has been depicted in Fig. 1.5.

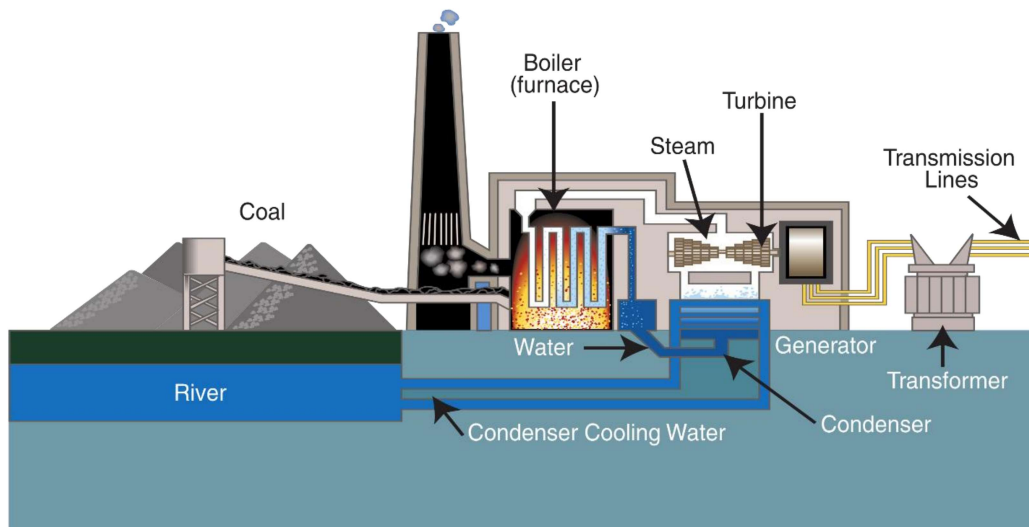


Fig. 1.5. Schematic representation of complete process involved in the thermal power plants. (Source: Tennessee Valley Authority 2023)

The raw coal first pulverized into powdered form so that the complete combustion can be ensured. After that, the pulverized coal transferred to the boiler (furnace) having duct arrangements through which water can pass. The burning of coal produces heat that converts water inside the duct into steam of high temperature and pressure. The operating temperature of boiler usually kept below 600 degrees Celsius. The high temperature and pressure steam directed towards the turbine blades that results in the rotation of the turbine. The rotating turbine cuts the magnetic field inside the generator that results in the generation of electricity. The utilized steam again sends to condenser to transform into water that can be further reutilized for steam production.

The electricity production is a continuous process for that a regular source of water supply, and coal supply is required. At the same time, it is necessary to take care of the removal of coal ash produced during the coal burning. For the removal of coal ash, the boiler is attached with the ash handling units for various types of coal ash. The generated coal ash is broadly classified into fly ash and bottom ash. The fly ash has major contribution in coal ash than that of the bottom ash (10-20%). The bottom ash, also known as bed ash is settled down at the bottom of the boiler due to its own weight and thus collected from the bottom of the boiler. Whereas, fly ash being lightweight in nature required multiple separation units to separate it from flue gases, therefore, it is collected from the economiser, air-preheater and electrostatic precipitator (ESP). The majority of the fly ash is usually collected in the electrostatic precipitator unit. Two separate ash handling units for fly ash and bottom ash disposal is required. The coal ash generated in the thermal power plants is handled through different types of ash handling system such as; (a) pneumatic ash handling system, (b) hydraulic ash handling system, and (c) mechanical ash handling system. These are discussed below.

**a) Pneumatic ash handling system**

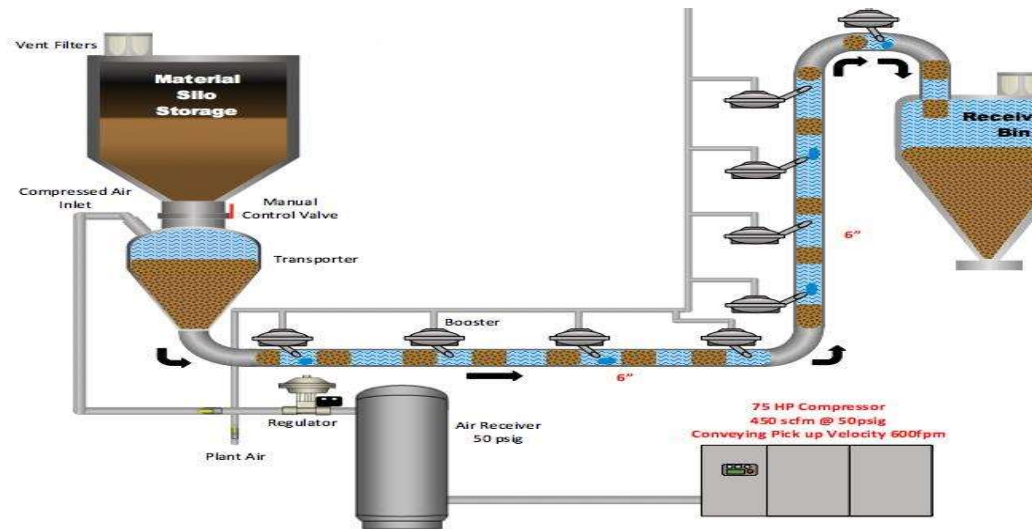


Fig. 1.6. Typical cross-sectional demonstration of Pneumatic ash handling system.  
(Courtesy: VAC-U-MAX)

The pneumatic ash handling system (PAHS) is very common in Indian thermal power plants. Based on the ash movement inside the pile, the Pneumatic system again bifurcated into lean, medium, and dense phase conveying system. The dense phase is widely accepted due to its high ash transport capacity. To ease transportation, the bottom ash needs pulverization because of the formation of large granular particles. The typical cross-sectional demonstration of the pneumatic ash handling system has been shown in Fig. 1.6. The ash first collected in the storage tank after burning, then allowed to enter into the transporter vessel with the help of manual control valve (dome valve). Once the vessel gets filled with ash, the dome valve should be closed. After that, the compressed air is allowed to enter the ash-filled vessel that needs to be moved to the other storage containers. In addition, boosters are also installed to enhance the continuous flow of ash and to avoid blockage. Once, the ash vessel gets empty, the same cycle is started again.

**b) Hydraulic ash handling system**

The hydraulic ash handling system is again divided into low velocity and high velocity system that has been depicted in Fig. 1.7. In this system, a flowing water channel is made to carry coal ash that is further connected to ash sump where the ash was allowed to settle. In the low velocity type, the ash was allowed to fall freely into the flowing water whereas in the high velocity system the ash was prewetted by water spray system.

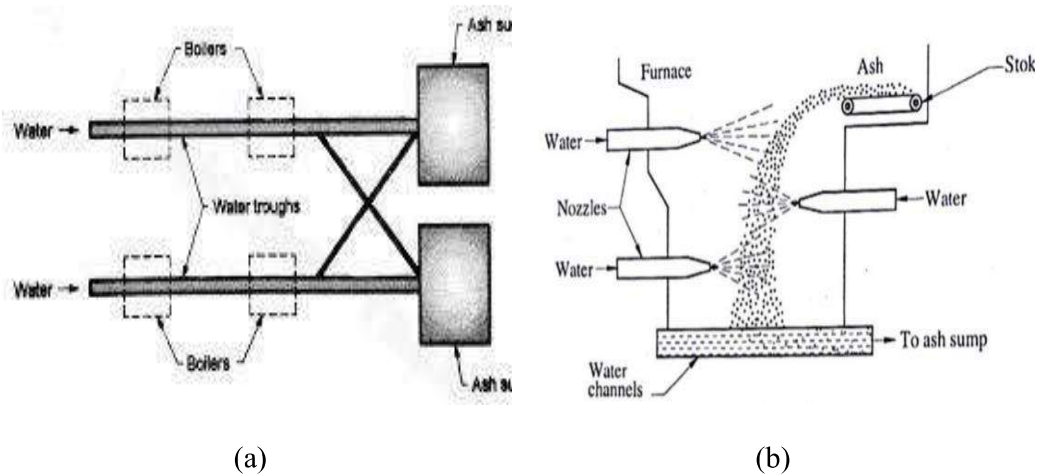


Fig. 1.7. Hydraulic ash handling system, (a) Low velocity system, and (b) High velocity system.

(Courtesy: Thermal Power Tech)

**c) Mechanical ash handling system**

The mechanical ash handling system is the simplest ash handling system that can be seen in Fig. 1.8. It is similar to low velocity hydraulic ash system with a slight modification of having a belt conveyor system along with the water channel. Here, the ash falls directly into the water reservoir which is deposited on the belt conveyor system at the bottom of the reservoir. With the help of this belt, the ash is transported to the bunkers from where it can be used in different applications.

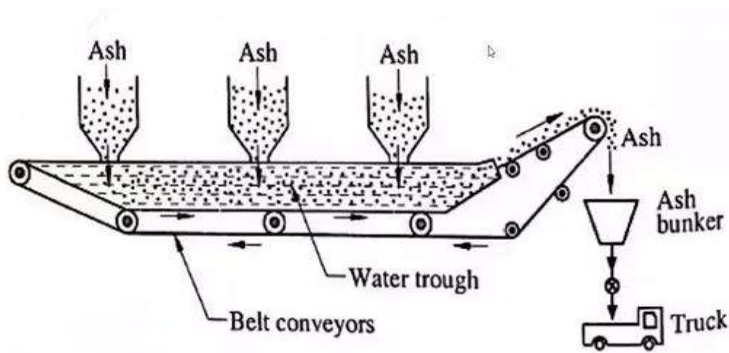


Fig. 1.8. Illustration of mechanical ash handling system.  
(Courtesy: Thermal Power Tech)

The ash collected into the silos is distributed for various industrial applications like cement, brick manufacturing, road and embankments etc. Since, the ash generation is a continuous process, the unutilized ash must be disposed of as early as possible so that the fresh ash could be stored into the silos. Hence, fly ash and bottom ash mix together with water to form a slurry and directly disposed into the pond near to the thermal power plant known as pond ash. Whereas, if the mixture of fly ash and bottom ash is dumped in dry form into the pond then it is called as mound ash (IS 3812- Part 2-2013).

## 1.2 AN OVERVIEW AND PROBLEM IDENTIFICATION

The production of coal ash from the thermal power stations creates alarming situations due to the increasing demand of electricity year after year. As per the current demand supply trend, this situation will continue for the upcoming 3-4 decades, particular in India. The utilization of coal ash in different sectors could be considered as one of the solution and multiple initiatives have already been taken towards this direction. The fly ash has a higher fraction in coal ash that possesses pozzolanic property that's why it has wider application than that of the other ashes. But this pozzolanic property vanishes when it comes in contact with water, thus fly ash must be utilized in dry form. But the

problem associated with this is that every thermal power plants have some certain capacity to store dry coal ash and since production of ash is a continuous process, it cannot be stored for a longer period of time. Hence, these accumulated ashes generally disposed to the nearby ash ponds using the appropriate ash handling system. The regular disposal of ash results in the formation of numerous ash dams/heaps and occupies huge quantity of land. In Fig. 1.4, it can be seen that the ash generated in the past 25 years has only utilization percentage of 55% on the other hand 45% of ash is still remaining in dumped state.

The dumping of ash near to the thermal power plant originates several environmental issues and observed frequent failures in the coal ash deposit during the rainy season. The total of seventy-six dumped ash dyke failures have been witnessed in the last decade (Kapoor and Raheja 2021). The summary of the recent major ash deposits failures has been tabulated in Table 1.1. These failures lead to the spreading of the ash slurry over large area of land that ultimately attributed to the destruction of agricultural crop/land, contamination of surface water bodies, destruction of houses of nearby human habitants, and make toxic environmental conditions. The failures mostly happen during the rainy seasons, because rain water gets absorbed into the ash due to its free draining behaviour and develops hydrostatic pressure. The ash embankments/dykes exist in deposits of several meters get disturbed due to the rain and apply hydrostatic pressure along with active pressure on the supporting walls which results in failure. The failure of ash dyke in Reliance Sasan ultra mega power project in India was occurred due to the collapse of the retaining wall that causes spreading of ash slurry approximately around 6 km in longitudinal stretch. These types of ash failures were very common because of the destruction of the wall, bursting of slurry pipes, and overflow due to the heavy rainfall that can be seen in Table 1.1. Although the coal ash

has been utilized as a substitute of few Civil engineering materials but, it is restricted to a limited number of applications. In order to terminate the ash failures and reduce the harmful impact to the environment, the areas of application should be expanded for its bulk utilization. The engineering characteristics of coal ash must be investigated such as physical, chemical, and morphological behaviour, it would help in the selection of specific ash for any particular application.

In addition, the geotechnical properties and the dynamic properties must be explored, so that the complete analysis on the materials can be done prior to the field application. Based on these results and analysis, a concrete recommendation of coal ash for a particular application could be done in pavement layers (base/sub-base/subgrade) or in embankment fills or as foundation material which helps in the bulk utilization of the coal ash.

Table 1.1.1. Past reported failure case study of ash deposits between 2019 to 2021 (Kapoor and Raheja 2021).

<b>Name of Power station</b>	<b>Date of Incident</b>	<b>Area affected</b>	<b>Peoples affected</b>	<b>Fly ash discharged</b>	<b>Causes of failure</b>
Essar TPS	7 <sup>th</sup> August 2019	50 ha	500 Farmers	1 Lakh tonnes	Substandard construction of dyke and Heavy rainfall
Bokaro TPS	12 <sup>th</sup> September 2019	18 ha	More than 20	-	Heavy rainfall
Vindhyachal TPS	6 <sup>th</sup> October 2019	53 ha	-	2.25 Lakh tonnes	Heavy rainfall
Reliance Sasan Ultra Mega Power Project	10 <sup>th</sup> April 2020	80 ha	6 Casualties	-	Collapse of wall
Anpara TPS	Continuous supply of ash into Rihand reservoir	-	-	21% of total fly ash	Overflow due to rainfall
Talcher TPS	6 <sup>th</sup> March 2020	-	12 Families	-	Bursting of slurry pipeline
North Chennai TPS	24 <sup>th</sup> August 2020	-	60 - More than 100 households	-	Bursting of slurry pipeline
Kahalgaoon Super TPS	7 <sup>th</sup> November 2020 & 21 <sup>st</sup> January 2021	80.8 ha	-	-	Overflow of accumulated residual water

### **1.3 STRATIFICATION PHENOMENON**

The creation of ash ponds acquires a significant amount of valuable land. According to the case study of Kolaghat Thermal Power plant, it has been found that for one megawatt of electricity generation normally 1 acre of land is needed throughout the entire life of the power plant (Dasgupta et al. 2011). The ash slurry is normally discharged through continuous supply for a certain time period that results in ash deposits of multilayer thickness. During a single delivery period, a slurry of coal ash is deposited in the uniform layers that range in thickness from 2 to 5 cm (Ishihara et al. 1980). The average height of ash dumped in the pond is around 40 to 60m above the natural ground level which has achieved by combining a lift of 7m width and 5 to 6m height (Mohanty et al. 2020). Basically, the conventional wet/dry disposal technique used to dump coal ash is responsible for the stratification/layering of the ash deposits. The fundamental properties of the generated coal ash highly dependent on the type of coal used for burning. Hence, each layer of deposition may vary in their particle size distribution, density, settlement behaviour, etc. that ultimately affects its load transfer mechanism. Therefore, it is significant to consider this stratification of various ash layers for sustainable application of coal ash. In the present study, the stratification has been implemented by considering the naturally available soil overlain by coal ash layer. Because in field application, the coal ash usually applied over the existing soil, hence their interaction needs to be carefully examined.

### **1.4 OBJECTIVES**

The objectives of the present study are divided into multiple stages considering the aforementioned problems associated with the coal ash production. The objectives are listed as follows:

- To study the physical, morphological, mineralogical, chemical, and geotechnical characteristics of homogeneous soil and fly ash.
- To study the static strength characteristics of homogeneous and stratified soil-ash deposit under different controlled loading conditions.
- To study the dynamic characteristics of homogeneous and stratified soil-ash deposit under different relative compaction, confining pressure, frequency of loading, and amplitude of cyclic shear strain.
- To study the liquefaction potential of homogeneous and stratified soil-ash deposit under different relative compaction, confining pressure, frequency of loading, and amplitude of cyclic shear strain.
- To propose generalized relationships for liquefaction potential evaluation of homogeneous and stratified soil-ash deposit by energy method.
- To study the stiffness characteristics of homogeneous and stratified soil-ash deposit under low-strain condition.
- To develop empirical strain dependent modulus reduction and damping correlations for homogeneous and stratified soil-ash deposit.
- Performance of stratified soil-ash deposit as a pavement material.

## **1.5 SCOPE OF THE STUDY**

The scope of the present study has been discussed in a comprehensive manner after analyzing the aforementioned objectives of the study. As per the regulations issued by the ministry of environment forest and climate change, the coal ash production source near to Varanasi has been considered here, i.e., Grasim Industry Limited, Renukoot, (U.P), India. The pavement application of ash is usually done in layers, therefore the interaction of the existing soil with fly ash has been critically explored. The initial phase

starts with the physical and geotechnical characterization of both the source materials (fly ash and local soil). This experimental study will help in the classification and assessment of the engineering behaviour of the materials, so that its performance can be predicted under static loading conditions. Then, the presence of the hazardous element/compound was examined for the safe application of the material. Also, the morphology and specific chemical constituents present was investigated, so that their suitability in particular application can be recommended.

Furthermore, the homogeneous soils and stratified soil-ash deposits were investigated for its dynamic soil parameters and liquefaction potential by performing a series of strain-controlled cyclic triaxial test. These tests were conducted in large shearing strain condition, i.e., 0.3% to 1.5% under the loading frequency range from 0.3 Hz to 1 Hz. The cylindrical specimen was prepared at relative compaction of range 95% to 99%, using the moist tamping technique. In the same way, these all combinations were tested under saturated condition followed by consolidation incorporating the effective confining pressure between 70 kPa to 100 kPa. The cyclic triaxial test was conducted in controlled consolidated undrained conditions in order to explore the liquefaction potential of the materials.

Along with the dynamic soil properties, it is significant to have the normalized modulus reduction curve, in order to evaluate the seismic ground response of the present soil combinations. Hence, these combinations have also been investigated under low-strain conditions using bender element test. The tests were conducted in similar condition as like cyclic triaxial test, and the outcomes ( $G_{max}$ ) were incorporated to plot the normalized modulus reduction ( $G/G_{max}$ ) graphs. In addition, the model validation and correlation studies were developed to predict the values at the lower and higher side of the considered strain. The liquefaction potential was also investigated with the help

of energy method that simplifies the correlation between earthquake tremor and the resistance potential. The complete experimental investigation and analytical analysis results will help in the successful application of the layered soil-ash deposits not only in low seismic zone but also in high seismic areas.

## **1.6 ORGANIZATION OF THE THESIS**

The thesis has been organized into multiple chapters with detailed experimental analysis from basic to advanced. These chapters start with the general illustration of the problem and review of the past studies that have been done considering different materials and equipment. After this, the chemical and geotechnical characterization of the selected source material were carried out. Based on fundamental properties, the advanced experimental studies were conducted for different soil combinations. The brief description of each chapter has been incorporated in the subsequent sections.

**Chapter I** describes the background, motivation towards this research topic, objectives, and scope of the research.

**Chapter II** provides a review of the previous work on the physical, chemical, mineralogical, morphological, geotechnical, static, dynamic properties of different coal ashes, and stratified studies of different soil combinations, then summarized the research gap for further study.

**Chapter III** reported the source of sample collection and sample preparation technique used in the present study. All the experimental testing program for the static and dynamic study were demonstrated in pictorial representation. Also, the logic behind the consideration of various parameters were explained in this section. Along with that, the moist tamping technique, fundamental description of the cyclic triaxial test and bender element test, and testing procedure has been described in detailed.

**Chapter IV** presents the elemental, morphological and mineralogical composition of the source material using SEM, EDX, and XRD analysis. Also, reported the percentage fraction of different compounds present in the source material and its pH value.

**Chapter V** presents the outcomes of the geotechnical test conducted on the source materials in the laboratory. It includes the particle size distribution, classification, density behaviour, permeability and CBR results. The results were depicted in pictorial, graphical, and tabular form for better understanding.

**Chapter VI** investigated the shear strength parameters of the homogeneous and stratified soil-ash deposit under UU, CU, and CD triaxial conditions. The homogeneous and stratified soil-ash combination were tested under static condition under various triaxial stages (i.e. UU, CU, and CD). In addition, the results were compared with the past studies and analyzed with practical examples. This study was primarily conducted to determine the effect of drainage (drained/undrained) on the cohesion and angle of internal friction of the homogeneous and stratified soil-ash deposit.

**Chapter VII** discussed about the parametric study on the dynamic shear modulus of the homogeneous and stratified soil-ash deposit. The strain-controlled cyclic triaxial test was conducted under consolidated undrained conditions to determine the dynamic shear modulus of all the soil combinations. Along with that, the influences of various independent parameters such as shearing strain, loading frequency, effective confining pressure, and relative compaction have also been investigated. This chapter also includes the liquefaction potential evaluation of the homogeneous and stratified soil-ash deposit by energy approach.

**Chapter VIII** presents the laboratory study on the damping behavior of the homogeneous and stratified soil-ash deposit under large shearing strain. This chapter comprises, the damping characteristics of all the soil combination considering

symmetrical hysteresis loop, asymmetrical hysteresis loop and modified ASTM approach. This study also incorporates the various independent testing parameters to determine the damping response of the homogeneous and stratified soil-ash deposit.

**Chapter IX** described the maximum shear modulus of all the soil combinations, which was analyzed using bender element test. In addition, these tests were conducted in dry, saturated, and unsaturated conditions. The outcome of the present experimental study has been analyzed by three different travel time determination method (such as; Peak to Peak, Start to Start, and Trough to Trough). All the shear modulus and damping ratio of the homogeneous and stratified soil-ash deposit were normalized with the maximum shear modulus values and fitted in the hyperbolic model to get the generalized equations for the present materials.

**Chapter X** described the thickness determination of the flexible pavement of both the homogeneous and stratified soil-ash arrangements using IITPAVE software. Furthermore, the stratified arrangements were also checked with different forms of reinforcement placed in between fly ash and local soil under soaked and unsoaked conditions.

**Chapter XI** summarizes the research and presents the major findings and limitations of the current study and further future research directions are suggested.

Finally, the references used in this study are organized alphabetically.

