ASSESSMENT OF ENVIRONMENTAL AND ECONOMIC IMPACTS OF IMPORTED COAL AND NATURAL GAS BASED THERMAL POWER PLANTS IN INDIA

By

KULDEEP KUMAR AGRAWAL

COLLEGE OF MANAGEMENT AND ECONOMIC STUDIES

DR. SURESH JAIN
ASSOCIATE PROFESSOR
DEPARTMENT OF NATURAL
RESOURCES

DR. ARVIND JAIN
ASSISTANT PROFESSOR
COLLEGE OF MANAGEMENT
& ECONOMIC STUDIES

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Kuldeep Kumar Agrawal

DECLARATION

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material, which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Kuldeep Kumar Agrawal
Dated: 05.11.2012

THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on "**Assessment of Environmental and Economic Impacts of Imported Coal and Natural Gas Based Thermal Power Plants in India**" submitted by Kuldeep Kumar Agrawal to the **University of Petroleum & Energy Studies** for the award of the degree of Doctor of Philosophy (Management) is a bona fide record of the research work carried out by him under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

Dr. Suresh Jain (External Guide)
Associate Professor
Department of Natural Resources, TERI University, New Delhi
Place: New Delhi Dated: 5th November 2012

Dr. Arvind Kumar Jain (Internal Guide)
Assistant Professor and Head,
College of Management & Economic Studies, UPES
Place: Dehradun Dated: 5th November 2012

Dr. Hiranmoy Roy (Internal Co-Guide)
Assistant Professor
College of Management & Economic Studies, UPES
Place: Dehradun Dated: 5th November 2012

CONTENTS

EXECUTIVE SUMMARY

India accounts for more than 17% of world's population i.e. about 1.2 billion people. It is very challenging for India to provide sufficient energy supplies to all the consumers at an equitable cost. India's energy use has increased 16 times in the last six decades, and the installed electricity capacity by 84 times. Worldwide, electricity conventionally produced in thermal power plants from coal, natural gas and oil accounts for about 67% of the electricity produced and in India, it is about 65.7% (as per the Central Electricity Authority). The other sources of electricity generation are nuclear power plants, hydro power plants and other renewable energy sources like wind and solar energy. Although, the main source of electricity generation in India is coal, contributing about 55.5% of the electricity generation, but natural gas also has a significant share of about 9.13%. As thermal energy generation process requires combustion of fuel either coal or natural gas and these emit certain amount of toxic pollutants into the atmosphere which further degrade the environment and human health. The environmental impact assessment studies associated with electricity generation from coal and natural gas in Indian conditions are very limited. If these emissions continue with the present rate, the condition in future would further worsen the problem of global warming and climate change. India proposing to promote coalmine power stations using domestic coal; whereas, coastal power stations should use either imported coal or natural gas. Hence, it is important to assess which is a better option for electricity generation posing least

damage to environment and more cost effective between the two fuel types i.e. imported coal and natural gas.

Presently, coal and natural gas contributes major shares for electricity generation in India and it has been estimated that similar trend would follow in future.

Life cycle analysis (LCA) has been used as an *analytical technique* (quantitative research methods) for assessing environmental impacts. The LCA combines analytical studies (such as assessment of the mass flows and emissions) in specific processes and experimental research to define the environmental profile of a process/technology/fuel type used. The economic cost has also been calculated using life cycle costing approach which includes per unit electricity generation coast along with hidden cost due to climate and human health damage.

In LCA methodology, CML 2001 and Eco-Indicator 99-H methods have been used to quantify environmental impacts. CML 2001 is based on problem oriented approach and quantify impacts, whereas, Eco Indicator 99 (H) is based on damage oriented approach which gives results for various major impact categories such as carcinogens, respiratory organics, respiratory inorganic and climate change. The study reveals that imported coal has more impacts (nearly1.9 times) as compared to natural gas in terms of Global Warming Potential (GWP) and Climate Change Potential (CCP) due to various emissions such as CO_2, CH_4 and N_2O. The total GWP from upstream and combustion processes due to natural gas and imported coal thermal power plants from both the methods (CML 2001 and Eco-Indicator 99-H) are nearly 0.577 kg CO_2 eq/kWh and 1.122 kg CO_2 eq/kWh, respectively; whereas, around 455 and 960 g CO_2 eq/kWh from combustion of natural gas and imported coal, respectively. If we compare the overall acidification potential due to combustion of imported coal without FGD technology, it has approximately 3.7 times more acidification potential as compared to imported coal with FGD technology; whereas, combustion of natural gas has 0.87 times less potential as compared to imported coal with FGD technology. The ecotoxicity impacts in terms of PAF due to combustion of imported coal without FGD technology, it has approximately 1.7 times more impacts as compared to imported coal with FGD technology; whereas combustion of natural gas has 3.5 times less impacts in terms of PAF as compared to imported coal with FGD technology. The uncertainty analysis using Monte Carlo method was used and it has been observed coal thermal power plant with FGD is better as compared to coal thermal power plant without FGD for ecosystem and human health, even though more resources may be required for operation and maintenance of this new technology with > 99% certainty.

Economic analysis in terms of life cycle costing (LCC) which comprises of cost of plant design, installation, operation & maintenance, fuel cost and revenues from electricity generation. The estimation was made using the annuity method with a real interest rate of 14% per annum and with a fixed price level as of January 2009. With plant load factor (PLF) of 80 %, the generation costs for coal based electricity are ` 3.66/kWh and for gas based electricity ` 4.63/kWh. In order to study the impact of changes in the input data in economic analysis, a sensitivity analysis has been carried out. It reveals that the increase in cost due to FGD system in coal power plant is quite clear. The coal electricity is rather less sensitive to the changes of fuel price, whereas for natural gas per unit generation cost is more sensitive to gas price.

This study reveals that certainly natural gas is better option in terms of environmental aspects as compare to imported coal; however, electricity generation cost is higher than coal. By introduction of clean technologies like FGD reduces SO_x concentration comparable to natural gas emissions and still electricity generation cost is lower as compare to natural gas. Economic analysis shows that total cost (technology and hidden costs) for electricity generation from imported coal thermal power plant is ` 9.78/kWh in which, about 63% is due to hidden cost. The installation of FGD technology in imported coal thermal power plant (PC + FGD) results into reduction of hidden cost by 61% with an incremental cost of ` 0.14/kWh. Further, installation of CCS technology in imported coal thermal power plant (PC + CCS) results into reduction of hidden cost due to CO_2 by 18% with an incremental cost of ` 0.54/kWh; whereas, installation of FGD and CCS technology together in imported coal thermal power plant (PC + FGD + CCS) results into reduction of hidden cost by 79% with an incremental cost of ` 0.68/kWh. However, IGCC, SC and NGCC thermal power plants results into reduction of hidden cost by 81%, 22% and 81% with an incremental cost of ` 1.62/kWh, ` 0.12/kWh, ` 0.97/kWh, respectively, in comparison to PC.

In view of alternative technology assessment based on economic analysis, it appears that IGCC and NGCC are better technologies in terms of cost reduction by 81% for environmental and health damages by adding extra cost of ` 1.62/kWh and ` 0.97/kWh, respectively, in comparison to PC. However, IGCC plants are very few in operation in the world and feasibility of IGCC plants would depend significantly on the overcoming of the technology risk. In case of NGCC, the availability of natural gas is limited due to more demand from transport and domestic sector. After this, second choice is PC + CCS + FGD, but CCS technology has its own limitations. Third choice is PC + FGD, which is a better choice for reducing health damages (61% in comparison to PC) from SO_2, NO_x and PM_{10} by additional cost of ` 0.14/kWh.

LIST OF ABBREVIATIONS

ACP	Acidification Potential
As	Arsenic
BTU	British Thermal Unit
CC	Carbon Capture
CCNG	Combined Cycle Natural Gas
CCP	Climate Change Potential
CCS	Carbon Capture and Storage
CERC	Central Electricity Regulatory Commission
CFCS	Chlorofluorocarbons
CH4	Methane
CML	Centruum voor Milieukunde Leiden
CO	Carbon Mono Oxide
CO_2	Carbon Di Oxide
COD	Chemical Oxygen Demand
Cr	Chromium
DALY	Disability Adjusted Life Years
DB	Dicholorobenzene
DO	Dissolved Oxygen
EIA	Environment Impact Assessment
FG	Fuel Generator
FGD	Flue Gas Desulphurisation
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GHG	Green House Gas
GJ	Giga Joules
GTL	Gas to Liquid
GWP	Global Warming Potential

H_2S	Hydrogen Sulfide
H_2SO_4	Sulfuric Acid
HF	Hydrogen Fluoride
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
ISO	International Organization Of Standardization
Kcal	Kilo Calorie
Kgoe	kilogram Oil Equivalent
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
mg	Mili Gram
MWH	Mega Watt Hour
N_2O	Nitrous Oxide
NAPCC	National Action Plan on Climate Change
NEP	Nutrient Enrichment Potential
NG	Natural Gas
NH_3	Ammonia
Ni	Nickel
NOX	Nitrogen Oxide
O&M	Operation and Maintenance
PAF	Potentially Affected Fraction
PAH	Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyl Compounds
PDF	Potentially Disappeared Fraction

PLF	Plant Load Factor
PM	Particulate Matter
PO_4	Phosphate
POCP	Photochemical Ozone Formation Potential
PPM	Part Per Million
PV	Photo Voltaic
RES	Renewable Energy Sources
SCM	Standard Cubic Meter
SETAC	Society for Environmental Toxicology and Chemistry
SHR	Station Heat Rate
SNG	Synthetic Natural Gas
SOx	Oxides of Sulphur
SPM	Solid Particulate Matter
TPES	Total Primary Energy Supply
TPP	Thermal Power Plant
UHR	Unit Heat Rate

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

India accounts for more than 17% of world’s population i.e. about 1.2 billion people. It is very challenging for India to provide sufficient energy supplies to all the consumers at an equitable cost. India’s energy use and installed electricity capacity has increased by 16 times and 84 times respectively in the last six decades. Table 1.1 provides the comparison of Indian energy scenario with other regions of the world in terms of total primary energy supply (TPES), which has been normalized with respect to GDP and population for the year 2008 (OECD, 2010). It has been observed that India’s energy usage was the fifth highest in the world, and the lowest in terms of energy usage per capita i.e. 566 kWh. Energy is an important issue in today’s world, not only for the GDP of a country but also for the climate change mitigation. In recent years, India’s energy consumption has increased at a relatively fast rate due to population growth and economic development, even though the base rate may be somewhat low. With an economy projected to grow at 8-9% per annum, rapid expansion and improving standards of living for millions of Indian families, the demand is likely to grow considerably.

Electricity is one of the forms of energy, which is a necessary requirement for growth and development of the world in today’s industrial era. Worldwide, electricity conventionally produced in TPPs from coal, natural gas and oil accounts for about 67% of the electricity produced (IEA, 2011), and in India, it is about 65.7% (as per the Central Electricity Authority). The other sources of electricity production are nuclear power plants, hydro power plants and other renewable energy sources like wind and solar energy. Although, the main source of electricity generation in India is coal, contributing about 55.5% of the electricity generation, but natural gas also has a significant share of about 9.6% (IEA, 2011). Other sources of electricity generation in India are diesel (0.6%), nuclear (2.6%), hydro (20.9%) and other renewable energy sources (10.9%) as shown in Table 1.2.

Table 1.1: Comparison of Indian Energy Scenario with the World[1]

Country/Regions	Population (millions)	GDP per capita (PPP) 2000USD	TPES per capita (kgoe)	TPES/GDP (kgoe-2000USD)	Electricity Consumption/ capita (kWh)	kWh/S-2000 PPP
World	6688	9549	1803	0.19	2782	0.29
OECD	1190	27620	4560	0.17	8486	0.31
Middle East	199	8191	2990	0.37	3384	0.41
Former USSR	285	8996	3650	0.41	4660	0.52
Non OECD Europe	53	10471	2010	0.19	3378	0.32
China	1333	8311	1600	0.19	2471	0.30
Asia***	2183	4013	650	0.16	719	0.18
Latin America	462	8522	1240	0.15	1956	0.23
Africa	984	2540	670	0.26	571	0.22
India	1140	3781	540	0.14	566	0.15

*** Asia excludes China but includes India

It is clear from Table 1.2 that TPPs are the main source of electricity production and they derive energy from fossil fuels. As thermal energy generation process requires

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[1] Source: OECD, 2010

combustion of fuel, either coal or natural gas, and these emit certain amount of pollutants into the atmosphere.

Table 1.2: Overview of Electricity Generation in India[2]

All India	**Thermal**				**Nuclear**	**Hydro (Renewable)**	**RES @ (MNRE)**	**Grand Total**
	Coal	**Gas**	**Diesel**	**Total**				
MW	102863.38	17742.85	1199.75	121805.98	4780	38748.40	20162.24	185496.62
(%)	55.5	9.6	0.6	65.7	2.6	20.9	10.9	100

Various studies have been carried out in different parts of the world for assessing environmental damage caused due to burning of coal and natural gas as fuel for generating energy (Odeh and Cockerill, 2008; Proops et al., 1996; Phumpradab et al., 2009). The environmental impact assessment studies associated with electricity generation from coal and natural gas in Indian conditions are very limited. The demand of electricity for development of industries, transport infrastructure, agriculture and rapidly growing urban systems is increasing at a fast rate. Figure 1.1 shows sector wise energy demand during 2010-11 in India and clearly indicate that industries are consuming almost 40% of the total energy followed by domestic consumption i.e. 29%. To fulfill this increasing demand, more sources must be explored for electricity generation. As electricity generation from renewable energy sources is a new and developing field, hence, the rising demand of electricity will put pressure on the fossil fuel reserves for electricity generation in TPPs. New TPPs will be installed and various types and quality of fossil fuels will be burnt in these TPPs, but coal and natural gas will be sharing the

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[2] Source: IEA, 2011

maximum amount of fossil fuels used in these TPPs. In the process of electricity generation, various toxic pollutants are released into the atmosphere, which further degrade the environment and human health (Lave and Seskin, 1972). We can measure the pollutant concentration by methods like chemical analysis of the samples or with the help of pollution measuring devices, but we can't directly relate the impacts caused by these pollutants. Also, the environmental damage caused by individual steps in the power generation process can't be quantified. If we can't quantify these things, we would not be able to reduce the environmental damage due to our power generation process to a significant amount; the reason is that we don't know exactly where to improve. So, tools like LCA could be used to resolve this problem and would help in better decision making in terms of environmental as well as economic impacts.

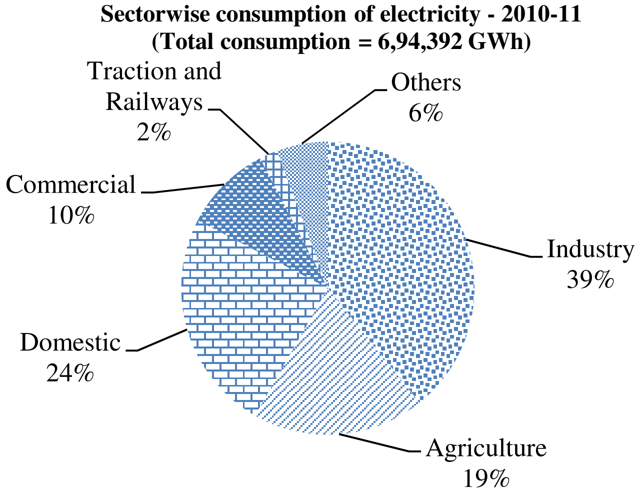

Figure 1.1 : Sectorwise Energy Demand During 2010-11[3]

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[3] Source: CSO, 2012

1.2 NEED FOR THE RESEARCH

India is the 4th largest power generation market in Asia and the 6th largest in the world. It has been observed that about 50% of the total CO_2 emissions are from the power sector and at the same time, India is trying to generate more power using fossil fuel, but wants to reduce its GHG emissions; and both things can't go at same time. In June 2008, India came up with the National Action Plan on Climate Change (NAPCC) due to huge intercontinental pressure to decrease its GHG emissions. At present, in India, approximately 65.7% of electricity generation is from coal, oil and natural gas (IEA, 2011). If these emissions continue to increase with the present rate, the condition in future would further worsen the problem of global warming and climate change. It has been observed that coal has approximately 40-50% more GHG emissions as compared to natural gas during electricity generation (Meier, 2010). India is proposing to promote coal mine stations using domestic coal; whereas, coastal stations should use either imported coal or natural gas. Hence, it is important to assess which fuel is better in terms of environmental and economic impacts, as well as efficiency for electricity generation in future.

It is imperative that actions are needed to address the conflicting objectives of energy security, economic growth and environmental protection; and also in resolving the difference between these. The need of the hour is to find ways to safely continue using fossil fuels and simultaneously develop alternate sustainable sources of energy.

It is a tough balancing act with issues of –

- Relatively few sustainable conventional energy solutions

- Limiting water and soil pollution, and reducing greenhouse gas emissions
- Difficulties inherent in bringing new technologies on stream quickly and ensuring their early uptake.

1.3 BUSINESS PROBLEM

It has been observed that global energy demand would increase by about 50% by 2035 as estimated by U.S. Energy Information Administration. It has been estimated that oil, coal and natural gas is expected to supply 79.2% of the global energy, only slightly less than today's (83.7%) (US EIA, 2011). However, at present in Indian scenario, approximately 65.7% of energy generation is from coal, oil and natural gas (IEA, 2011). Meier (2010) observed that coal and oil have approximately 40% more GHG emissions as compared to natural gas during electricity generation. If these emissions continue increasing with the present rate, the situation in future would further aggravate the problem of global warming resulting into climate change and environmental degradation. Hence, there is a crucial need for the transfer of technology and development of suitable financial mechanisms for determining a better fuel in terms of efficiency for electricity generation. Before analysing the relevance of a better option in terms of environment and economy, some crucial questions need to be answered in this context;

- What would be the various environmental and economic impacts due to combustion of imported coal and natural gas in thermal power plants?
- Which is a cost effective and better option for electricity generation posing least damage to environment: imported coal or natural gas?

1.4 RESEARCH PROBLEM

The study addresses the problem to identify the better fuel between imported coal and natural gas from environmental and economic considerations. Presently, coal and natural gas contribute major shares for electricity generation in India, and it has been estimated that similar trend would follow in future.

1.5 SCOPE OF THE STUDY

The scope of the present study is to analyze various environmental impacts on human health and ecosystem quality from combustion of imported coal and natural gas thermal power plants during electricity generation in India using life cycle approach. This study also assesses the life cycle cost of electricity generation from thermal power plants.

1.6 OBJECTIVES OF THE STUDY

Following are the research objectives for this study

- To carry out environmental and economic impact assessment of imported coal and natural gas thermal power plants using life cycle approach.
- To carry out comparative assessment of imported coal and natural gas thermal power plants on various environmental and economic parameters.

1.7 RESEARCH QUESTIONS

▪ What are the various parameters which impact environmental and economic aspects due to imported coal and combined cycle natural gas thermal power plant?

➔ This question tries to answer that what are the various factors which have environmental impacts (on human health and overall ecosystem quality) and life cycle cost for 1 kWh of electricity generation using life cycle approach.

- Which is a more cost effective and better fuel option between coal and natural gas for electricity generation posing least damage to environment?

  ➔ This question tries to answer that whether imported coal is better option as compared to natural gas or vice versa in terms of overall environmental damage and economic cost for 1 kWh of electricity generation.

1.8 BRIEF DESCRIPTION OF THE THESIS

Chapter 1 describes the energy scenario in India in comparison to global scenario, need of the research, business problem, research problem, scope, research objectives and questions.

Chapter 2 reviews the literature on environmental and economic analysis using life cycle approach and also explains why LCA is a better methodology for analysing long term environmental impacts at regional and global levels as compared to other impact assessment methods such as EIA.

Chapter 3 describes the research methodology used in this study which explains the research design used for collection of secondary data and methods used for assessment of environmental and economic impacts from both thermal power plants.

Chapter 4 presents the secondary data collected after preprocessing and conversions of parameters/factors as per functional unit defined in chapter 3 for final use in environmental and economic analysis.

Chapter 5 explains the results and discussions of environmental and economic analysis for both thermal power plants as well as brief summary.

Chapter 6 presents the conclusions, recommendations, limitation and future scope of work.

CHAPTER 2: LITERATURE REVIEW

2.1 ENERGY SCENARIO IN INDIA

The all India cumulative installed capacity under various utilities as on 31.08.2012 was 207006.04 MW. India’s fuel mix consists of 57% of coal, 9% of natural gas, 19% of hydropower, 12% of renewable power, 2% of nuclear and the rest is oil (CEA, 2012). It is obvious that coal based generation dominates the variety and therefore, is a foremost cause of carbon dioxide emissions in India. Hence, there exists scope for reducing the CO_2 emissions by application of life cycle approach in environmental impact assessment of power plants in India.

Table 2.1: All India electric power generation installed capacity (MW)[4]

Sl. No.	**Region**	**Thermal**				**Nuclear**	**Hydro (Renewable)**	**R.E.S.@ (MNRE)**	**Total (MW)**
		Coal	Gas	Diesel	Total				
1	Northern	29923.50	4671.26	12.99	34607.75	1620.00	15423.75	4437.65	56089.15
2	Western	42479.50	8254.81	17.48	50751.79	1840.00	7447.50	8146.69	68185.98
3	Southern	23032.50	4962.78	939.32	28934.60	1320.00	11338.03	11769.32	53361.95
4	Eastern	22337.88	190.00	17.20	22545.08	0.00	3882.12	410.71	26837.91
5	N. Estn	60.00	824.20	142.74	1026.94	0.00	1200.00	228.00	2454.94
6	Islands	0.00	0.00	70.02	70.02	0.00	0.00	6.10	76.12
7	All India	117833.38	18903.05	1199.75	137936.18	4780.00	39291.40	24998.46	207006.04

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[4] Source: (CEA, 2012)

As power generation process involves combustion of fossil fuel, either coal or natural gas and releases significant amount of pollutants into the atmosphere, which promote to degrade the environment and human health. The environmental impact assessment studies associated with electricity generation from coal and natural gas in Indian conditions are very limited and not specific to thermal power generation. If these emissions continue with the present rate, the condition in future would further worsen the problem of global warming and climate change. India proposes to promote coal mine stations using domestic coal; whereas, coastal stations should use either imported coal or natural gas. Hence, it is important to assess which fuel is better in terms of environmental and economic impacts, as well as efficiency for electricity generation in future.

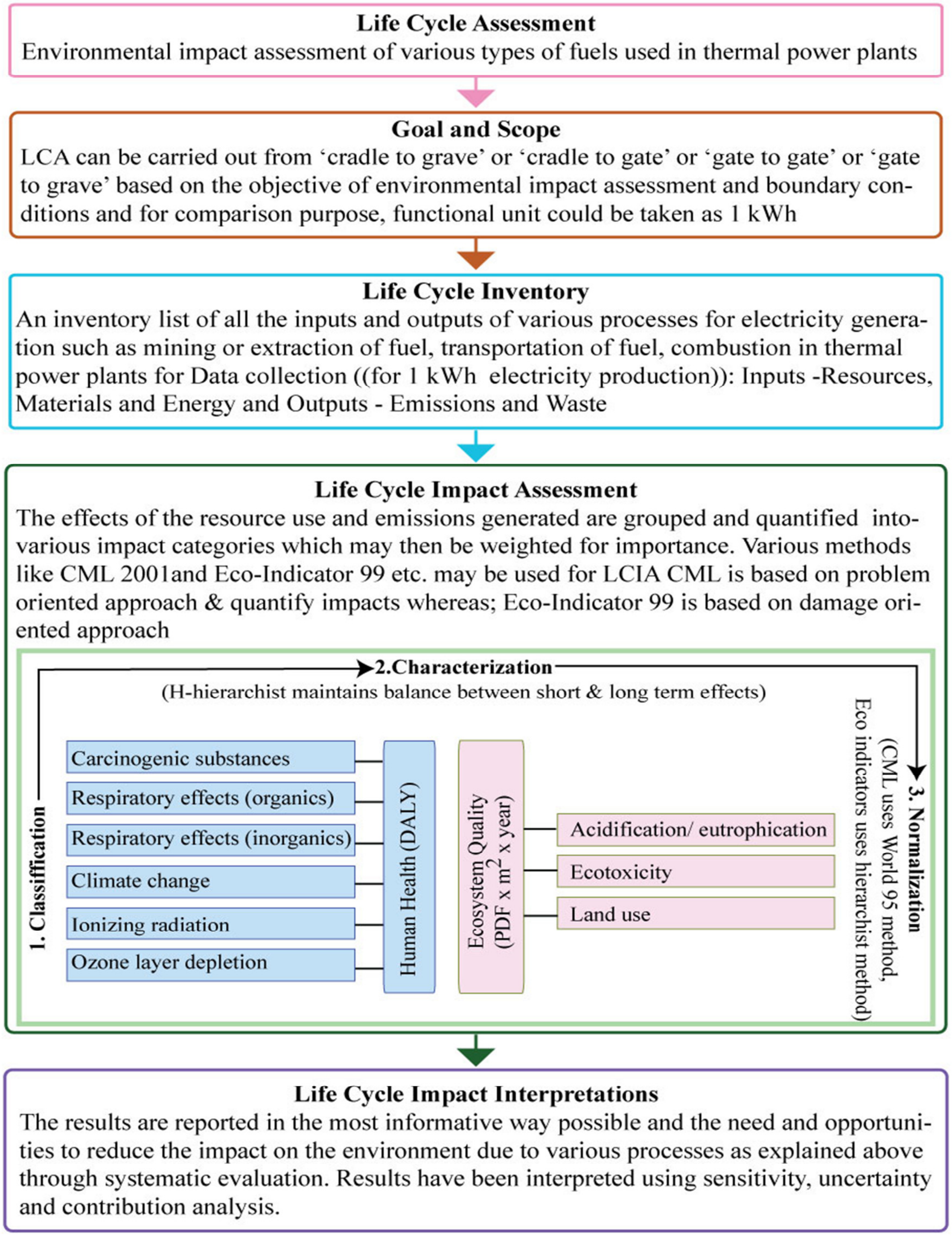
2.2 LIFE CYCLE ANALYSIS

LCA is a technique and approach to assess the overall impacts of any product, process or service for a specified aim. It may be environmental LCA or economic LCA based on the desired outcomes of the study. LCA is defined as a methodology, which assesses the environmental aspects and potential impacts throughout a product’s life from raw material acquisition (cradle) through production, use and disposal (grave) (ISO 14040, 2006). The ISO provides guidelines for conducting an LCA within the series of ISO 14040 and 14044 (Horne et al., 2009; Jensen et al., 1997). The various phases in LCA for measuring environmental impact assessment from electricity generation in TPPs have been shown in Figure 2.1.

LCA is a structured, internationally standardized method and management tool for quantifying the emissions, resources consumed and environmental and health impacts that are associated with processes/services/technology (ISO 14040 and 14044, 2006). There are various methods (for e.g. environmental impact assessment (EIA), life cycle analysis etc.) used for assessment of environmental impacts from any project development or process. The most widely used method is EIA, which is a regulatory mechanism for impact assessment but it has its specific limitations (Safer-environment, 2009 and Manuilova et al., 2008). The LCA method has been selected based on following reasons for this study:

- The main difference between EIA and LCA that EIA is not having structured framework for assessing environmental impacts as well as methodology for analysis.
- EIA is not having standard methodology for analyzing various impact categories such global warming, acidification and human toxicity; however, LCA has international set guidelines and methodology for assessing various types of impacts which can be compared with other studies (Tukker, 2000).
- The EIA framework assess mainly localized impacts and also site and project specific; whereas, LCA works with international protocols defined under ISO 140040-44 standards and it helps in assessing impacts from local to global scale with more reliable results using quantitative techniques.

Aspects	**LCA**	**EIA**
Flexibility	Minimum	Flexible
Qualitative analysis	No	Yes
Quantitative analysis	Yes	Yes
Impact categorization	Standardized	Case by case
Impact locations	Primarily global & regional	Primarily local but variable
Standardization	International & custom variations	National and state



Life Cycle Assessment

Environmental impact assessment of various types of fuels used in thermal power plants

Goal and Scope

LCA can be carried out from ‘cradle to grave’ or ‘cradle to gate’ or ‘gate to gate’ or ‘gate to grave’ based on the objective of environmental impact assessment and boundary conditions and for comparison purpose, functional unit could be taken as 1 kWh

Life Cycle Inventory

An inventory list of all the inputs and outputs of various processes for electricity generation such as mining or extraction of fuel, transportation of fuel, combustion in thermal power plants for Data collection ((for 1 kWh electricity production)): Inputs -Resources, Materials and Energy and Outputs - Emissions and Waste

Life Cycle Impact Assessment

The effects of the resource use and emissions generated are grouped and quantified into- various impact categories which may then be weighted for importance. Various methods like CML 2001and Eco-Indicator 99 etc. may be used for LCIA CML is based on problem oriented approach & quantify impacts whereas; Eco-Indicator 99 is based on damage oriented approach

Life Cycle Impact Interpretations

The results are reported in the most informative way possible and the need and opportunities to reduce the impact on the environment due to various processes as explained above through systematic evaluation. Results have been interpreted using sensitivity, uncertainty and contribution analysis.

Figure 2.1: General LCA Framework Showing Various Phases of Environmental Impact Assessment from Electricity Generation in TPPs

2.3 USE OF LCA AND LCC FOR ELECTRICITY GENERATION

The life cycle of an electricity generation plant includes mining/extraction of fuel, transportation of fuel and other raw materials, construction, operation and decommissioning of TPPs. The LCA studies should scientifically and effectively address the environmental aspects of various processes used in TPPs. The goal and scope defines the boundary and details of LCA analysis. The scope, assumptions, description of data quality, methodologies and output of LCA studies should be clearly explained, which further helps in comparing results with other similar studies. LCA methodology ought to be acquiescent to annexation of new scientific findings and improvements in the state-of-the-art technology. The strength of LCA is in its approach to study in a holistic manner the whole process instead of focussing only on a few processes (Modahla et al., 2011). The results are also related for the use of a process, which allows comparisons between alternatives. LCA includes definition of goal and scope, inventory analysis, impact assessment and interpretation of results (ISO 14041, ISO 14042 and ISO 14043). LCA is a powerful tool, often used as an aid to decision making in industry and for public policy (Gaines and Stodolsky, 1997) and (SETAC, 1993). This section focuses on critical reviews of two aspects i.e. environmental and economic impacts using LCA and LCC approaches. The LCC helps in decision making for right investment in terms of managing overall economic impacts and technology selection for better environmental performance.

2.3.1 ENVIRONMENTAL IMPACT ASSESSMENT

Bergerson and Lave (2002) have studied brief historical review about LCA of power plants. Later Lave and Freeburg (1973), and Sagan (1972, 1974) performed the first comprehensive environmental impact analysis for power plants. They both found that coal posed significant environmental risks from mining, transportation, and electricity generation. It has been observed that oil and natural gas have much smaller environmental and health impacts as compared to coal. May and Brennan (2003) have studied application of data quality assessment methods to an LCA of electricity generation. They have observed that black coal has more impacts as compared to brown coal. This study has compared several methods but is not able to highlight what are the gaps in different methods and what has to be included for better comparison using LCA. However, Sampattagul et al. (2004) have carried out LCA of Lignite-Fired Power Plant with and without flue-gas desulfurization (FGD) system in Thailand. They have observed that the installation of the FGD system can reduce the acidification problem associated with lignite-fired plants by approximately 97%. Carpentieri et al. (2005) had studied an LCA of a Brayton/Hirn combined cycle fuelled with clean syngas produced by means of biomass gasification and equipped with CO_2 removal by chemical absorption that reached 33.94%, considering also the separate CO_2 compression process. It has been observed that CO_2 emission of the power plant was 178kg/MWh using Eco-Indicator 95. These results were compared with other studies after integrating coal gasification combined cycle (ICGCC) with upstream CO_2 chemical absorption (38%–39% efficiency, 130 kg/MWh specific CO_2 emissions). Koroneos et al. (2005) have studied environmental aspects of two types of aviation fuel, i.e. kerosene (presently used) and hydrogen. Production by natural gas steam reforming and production by renewable energy sources are examined.

Hydrogen is selected as a future alternative fuel because of the absence of CO_2 emissions from its use, its high-energy content and its combustion kinetics. The lifecycle of aviation fuel includes the production and use of the aviation fuel in different types of aircrafts. A large number of environmental burdens result from the operation of different hydrogen production routes. The LCA of hydrogen system indicates that the route of hydrogen production with the use of photovoltaic energy has the worst environmental performance than all the other routes. This is attributed to the manufacturing process of the photovoltaic modules that contribute highly to all environmental impact categories of the system. At the same time the overall efficiency of the photovoltaic systems is very low. Weisser (2007) has studied GHG emissions from electric supply technologies. He observed that changing from one fuel to another may be a good option while observing emissions (one aspect) only, but in terms of cost it may not be a good option. Koornneef et al., 2008 have studied the environmental impacts of three pulverized coal fired electricity supply chains with and without carbon capture and storage (CCS) on a cradle to grave basis using LCA approach. They have observed that due to CCS, the GHG emissions per kWh are reduced substantially to 243 g/kWh. This is a reduction of 78% and 71% compared to the sub-critical and state-of-the-art power plant, respectively. Odeh and Cockerill (2008) have studied the life cycle of the electricity generation plant including construction, operation and decommissioning. A simple model for predicting the energy and material requirements of the power plant is developed. Preliminary calculations reveal that for a typical UK coal fired plant, the life cycle emissions amount to 990 g eq. CO_2 /kWh of electricity generated. The majority of these emissions result from direct fuel combustion (882 g/kWh). Furthermore, upon investigating the influence of power plant parameters on life cycle emissions, it is determined that, while the effect of changing the load factor is negligible, increasing efficiency from 35% to 38% can reduce emissions by 7.6%.

Further, Phumpradab et al. (2009) have analyzed two technologies i.e. thermal and combined cycle power plant, for the potential environmental impacts in a "cradle-to-grave" process using LCA of natural gas TPPs in Thailand. The comparison reveals that the combined cycle power plant, which has a higher efficiency, performs better than the TPPs for global warming potential (GWP), acidification potential (ACP), and photochemical ozone formation potential (POCP), but not for nutrient enrichment potential (NEP), where the TPP is preferable. Campbell et al. (2011) have analysed the potential environmental impacts and economic viability of producing biodiesel from microalgae grown in ponds. They observed that with favourable soil conditions, present technology and high annual growth rates, it is economically viable to reduce GHG emissions in the transport industry in Australia by growing algae and processing it into biodiesel. However, Bernier et al. (2011) have studied optimal GHG emissions in natural gas combined cycle (NGCC) TPPs integrating LCA. The combined use of a process model, LCA and multi-objective optimization solved the problem of cost-effectively reducing the life cycle GWP of energy systems through the simultaneous optimization of process configuration and procurement decisions, including the possible mitigation of background emissions such as methane emissions in the natural gas supply chain. Further, Hoffmann and Szklo (2011) have studied the maturity and costs of the integrated gasification combined cycle (IGCC) technology, with and without carbon capture (CC), and assessed the effect of the technology risk on its economic viability. It has been observed that the inclusion of the risk in the economic analysis of IGCC plants raises the cost of CO_2 avoided from 36 US$/t$CO_2$ to 106 US$/t$CO_2$ in the case of Shell Gasifiers and from 39 US$/t$CO_2$ to 112 US$/t$CO_2$ in the case of GE gasifiers. Thus, the introduction of IGCC with CC on a wider scale faces huge uncertainties.

Further, Figure 2.2 shows a comparison of different energy sources for life cycle emissions (Meier, 2010). It has been observed that coal has the maximum global warming potential followed by oil, natural gas and others. This data would help India for better planning in terms of environmental impacts for future electricity generation but at the same time it will help in optimal utilization of resources like coal which is plentiful.

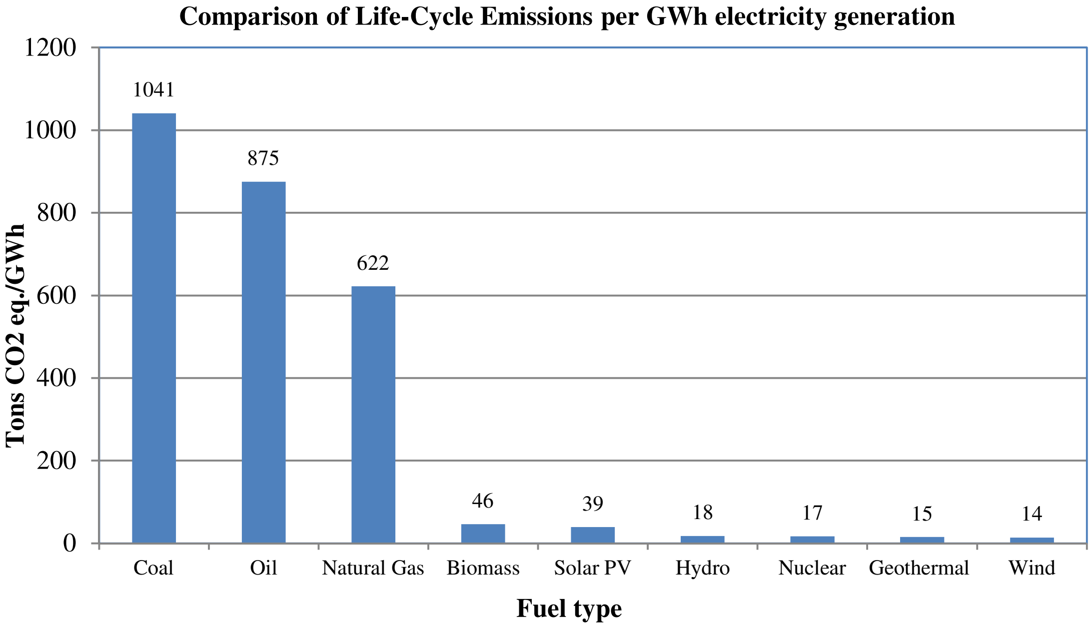


Figure 2.2: Comparison of Life-Cycle Emissions per GWh Electricity Generation from Various Fuel Types

2.3.2 ECONOMIC ASSESSMENT

Where economic aspects are concerned, there is the LCC approach for evaluating the economics of the life cycle of a product. The LCC can be expected to become a standard addition to LCA applications. The focus of this study is to consider not only the LCA outcome but also the LCC factors. LCA provides a broad view by generating a model which links the industry to be assessed through all its material and energy resource flows to other environmentally significant processes in the wider industrial network. The LCC was used to provide a comparison between alternative fuels to be used for power generating system. LCC, as a powerful analytical tool, examines the total cost of per unit generation. The LCC will comprise of cost design, installation, operation & maintenance, disposal and revenues. For an LCC study to be meaningful, data that reflects power generation systems in the country of interest (indigenous) must be used so that a detailed analysis can be carried out.

Koner et al. (2000) have studied life cycle energy costing for different electricity generators (photovoltaic generator, kerosene generator and diesel generator) used during load shedding. The parameters considered for calculation of the unit cost of energy were discount rate, inflation rate, IREDA loan facility to promote photo voltaic (PV), operation and maintenance cost of PV and fuel generator (FG) set and the associated fuel cost. It has been observed that the unit cost of PV electricity is comparable to or less than that of FG generated electricity at the present market prices. Battisti et al. (2006) have studied economic impact of some technical choices for gas–steam combined cycle power plants.

It has been observed that tools and the analysis shown in the paper can be a useful support to decision making in TPP planning and operation.

Jaramillo et al. (2007) have studied the GHG emissions, SO_x and NO_x life-cycle emissions of electricity generated with natural gas (NG)/ liquefied natural gas (LNG)/ synthetic natural gas (SNG) and coal. It has been observed that the current fleet of TPPs, a mix of domestic NG, LNG, and SNG would have lower GHG emissions than coal. It has also been observed that use of carbon capture storage for coal and a mix of domestic NG, LNG, and SNG would have very similar life cycle GHG emissions. Further, Jaramillo et al. (2008) have studied the life-cycle GHG emissions of coal- and natural gas-based Fischer-Tropsch (FT) liquids to compare production costs. It has been observed that the use of coal- or natural gas based FT liquids will likely lead to significant increases in GHG emissions compared to petroleum based fuels. In addition, the economic advantages of gas- to liquid (GTL) fuels are not obvious: there is a narrow range of petroleum and natural gas prices at which GTL fuels would be competitive with petroleum-based fuels. Jeong et al. (2008) have studied economic analysis of Korea's power plant utilities by comparing electricity generation costs from coal-fired power plants and LNG combined cycle power plants with environmental consideration. Further, Mantripragada and Rubin (2011) have studied the performance and cost of a liquids-only plant as well as a co-production plant, which produces both liquids and electricity. It has been observed that while liquids-only plants are more thermodynamically efficient, the most economical way that liquids can be produced from coal (in terms of the cost of liquid product) is in a co-production plant that also generates electricity for sale. There have been various studies related to techno-economic evaluation of coal to liquid (CTL) plants (Bridwater and Anders, 1991; Neathery et al., 1999; NETL/DoE, 2007; Steynberg and Nel, 2004; SSEB, 2006; Drummond, 2006; Williams et al., 2006; Reed et al., 2008). Figure 2.3 shows life cycle energy cost for electricity generation from various technologies which varies ±10-20% based on geographical locations as well as availability of resources (Donnelly et al., 2011). It has been observed that global energy demand would increase nearly 50% by 2035 as estimated by U.S. Energy Information Administration. It has been estimated that oil, coal and natural gas is expected to supply 79.2% of that energy, only slightly less than today's (83.7%) (US EIA, 2011). It has been observed from Figure 2.2 that coal, oil and natural gas are the major source of CO_2 emissions as compared to other technologies during electricity generation. Further, from US EIA report, if 79.2% energy would be supplied through use of coal, oil and natural gas, then the problem of global warming would further aggravate and result into climate change and environment degradation. Therefore, it is crucial for the transfer of technology and development of suitable financial mechanisms from developed world to nations who are still trying to find their equitable places for better and clean options of electricity generation.

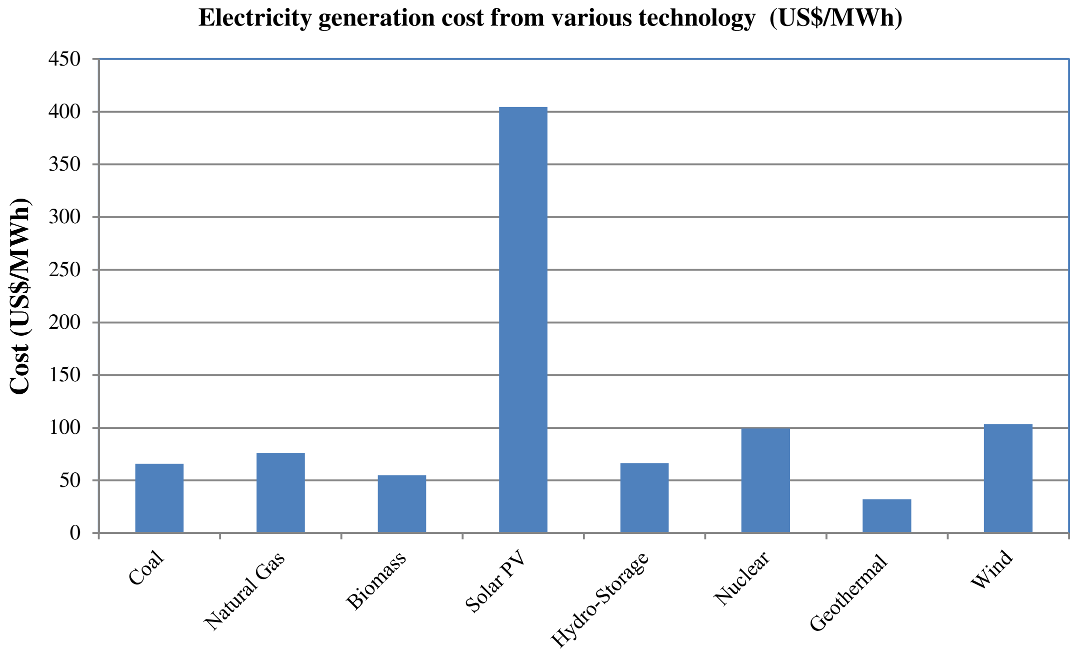


Figure 2.3: Electricity Generation Cost from Various Technologies Using LCC

CHAPTER 3 – RESEARCH METHODOLOGY

This section explains the research methodology adopted for this study. The research methodology has been divided into following steps:

3.1 RATIONALE OF THE STUDY

Increasing industrial and population growth has resulted in a surge in demand of electricity. The gap between demand and supply of electricity has widened in the recent past. In India, there are still many villages and areas that do not have access to electricity. These points highlight the need for expansion of power sector at a fast pace to provide electricity to all. However, before expanding the sector, environmentally and economically sustainable technologies need to be identified from the available alternatives. It has been observed in the literature that no such study has been carried out in thermal power plant sector that analytically assesses the available technologies in terms of environment and economic point of view for power generation by research community. LCA is one of the methodologies that can help in finding out environmentally sustainable technology in this sector. It would provide an effective and accurate means of evaluating an overall environmental impact as well as GHG emissions reduction strategies. The economic cost has been calculated using LCC approach which further helps in decision making for better environmental and cost-effective methods of electricity generation in long run to achieve the overall sustainability.

The problem has been identified based on literature review and discussion with experts working in the power sector.

Following points have been considered while selecting the area of research study:

- Domestic coal is in short supply and option available for costal thermal power plants is either natural gas or imported coal. Planning Commission (2000), Power and Energy Division, Government of India has also recommended that for coastal areas, imported coal or natural gas should be encouraged for electricity generation.
- Comparison has not been made between the available fuel options i.e. imported coal or indigenous natural gas as an alternative fuel to domestic coal for thermal power plants located near coastal areas in terms of environmental and economic impacts.
- No study has been carried out in India to estimate the overall impacts during life cycle of electricity generation from imported coal and indigenous natural gas on overall human health and ecosystem quality.

3.2 RESEARCH DESIGN

In this study, quantitative research design has been used for assessing environmental and economic impacts. The data has been collected from the secondary sources mainly from records maintained at thermal power plants and Eco-Invent data base. The LCA approach has been used as an analytical technique (quantitative research method) for assessing environmental impacts (Björklund, 2012). LCA combines analytical studies (such as assessment of the mass flows and emissions) in specific processes and experimental research to define the environmental profile of a process/technology/fuel type used. The economic cost has also been calculated using life cycle costing approach. Following steps have been used to achieve the research objectives of this study:

3.2.1 SITE SELECTION

Imported coal and natural gas are used as a fuel in thermal power plants which are located in coastal region for electricity generation. So, in this study, one thermal power plant is taken from Southern region (imported coal based: 2 × 600MW) and another thermal power plant was from Andhra Pradesh region (natural gas based combined cycle: 350 MW).

Coal Based Thermal Power Plant

The coal based thermal power plant of 1200 MW capacity is located in the South India near the coastal region and is very close to the port from which imported coal is supplied to the plant through wagons. The primary parts of a coal based thermal power plant are steam turbine, pulverised coal fired boiler and cooling tower. Hot air is mixed with pulverised coal and burns at high temperature (1100°C) in the boiler to generate superheated steam of 540°C and 17 MPa. This plant uses 100% imported coal as a fuel for electricity generation. The properties of imported coal and design configuration of this plant is provided in Tables 4.1 and 4.2.

Natural Gas Combined Cycle Thermal Power Plant

The NGCC thermal power plant of 350 MW is also located in South India near the coastal region and is very close to Krishna-Godavari (KG) basin from which natural gas is supplied to this plant. The primary parts of a NGCC power plant are gas turbine, heat recovery steam generator (HRSG) and steam turbines (Fig. 3.1). Compressed air is mixed with natural gas in the combustion chamber, and burns at high temperature (900 to 1500°C). This plant uses 100% natural gas share as fuel for electricity generation. The natural gas composition supplied from KG basin and design configuration of this plant is provided in Tables 4.3-4.5.

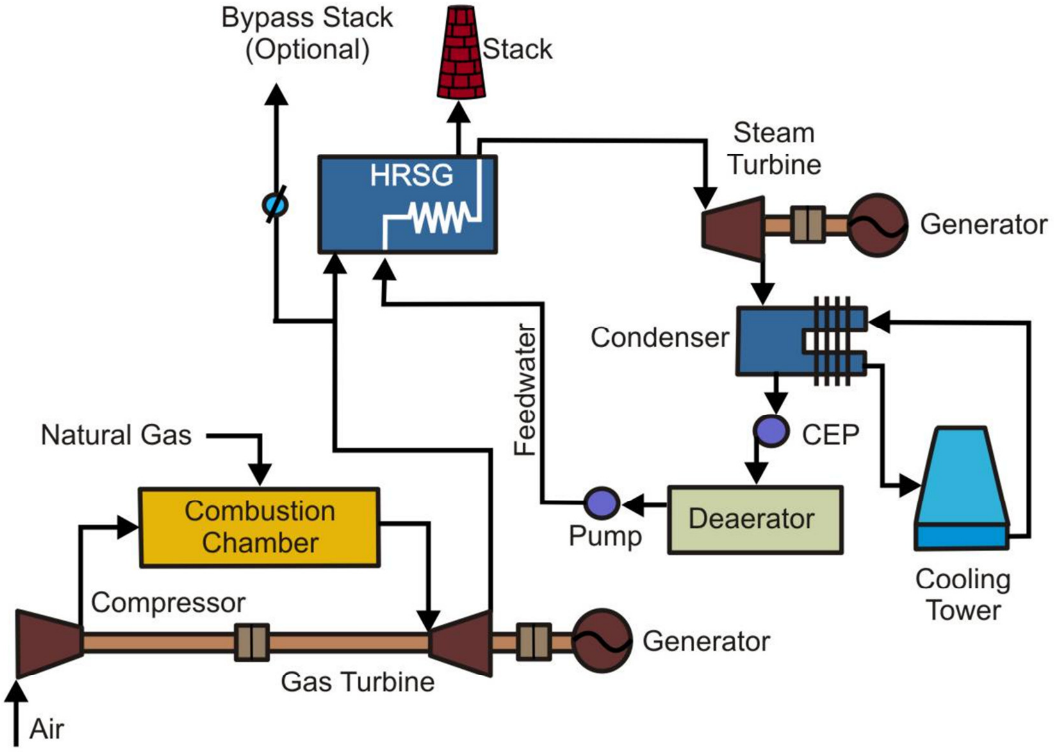


Figure 3.1: Schematic diagram for NGCC thermal power plant

3.2.2 DATA COLLECTION

The data has been collected on various *identified parameters* to assess the environmental and economic impacts of electricity generation from imported coal and natural gas combined cycle thermal power plants through various sources.

The secondary data has been collected from two major sources i.e. data from thermal power plants (actual sites by personal visits) and Eco-invent database. Data related to cost of electricity generation has been collected for the year 2011. Eco-invent version 2.2 data has been used for upstream processes, both for imported coal and natural gas; whereas, transportation details of fuel have not been included due to non-availability of data. Data has been collected using *spread-sheets* (sample spread-sheet has been provided in appendix A, Table A.1) from both plant sites by personal visits for resource consumption; air emissions, wastewater and solid waste and plant design for the year January 2011 to December 2011 (as provided in appendix B in Tables B.1 to B.3). Data was converted into usable forms after standard conversions. Data related to environmental impact assessment has been collected for all the pollutants from the thermal power plants in terms of air emissions, wastewater and waste (solid and liquid) as per compliance given by Central Pollution Control Board based on the Environment (Protection) Act, 1986 for all pollutants.

Direct method approach has been adopted for data collection based on averaging, which gives almost actual heat rate because coal/natural gas consumption measurement is fairly accurate if taken over a month/year.

- Step 1 - All design data such as turbine heat rate, boiler efficiency and basic history of thermal power station has been collected from station authorities and unit heat rate (UHR) is evaluated with respect to unit capacities at 100% plant load factor (PLF).

- Step 2 - Monthly operating data such as gross generation, total coal consumption, coal/gas average gross calorific value (GCV), specific oil consumption and oil GCV have been collected from thermal power station authorities based on which operating station heat rate for each month was calculated. Further, weighted specific coal consumption, weighted specific natural gas, weighted GCV of coal and weighted GCV of natural gas are computed yearly for calculating yearly station heat rate (SHR).
- Step 3 - Operating SHR thus calculated was then compared with respect to design SHR and percentage deviation is found to give an idea of performance of the station as a whole as per Step 2.

3.2.3 ENVIRONMENTAL IMPACT ASSESSMENT

Impact assessment is a method to characterize the nature and magnitude of health risks to human beings and ecological receptors such as birds, fish, and wildlife from toxic emissions (from air emissions, wastewater and solid waste/hazardous waste) and other stressors that may be present in the environment. Environmental risk assessments typically carried out for human health and ecosystem quality. This method would assess the incidence and degree of human and ecological exposures to various toxic chemicals for current and future scenario.

In general, for measuring risk due to various toxic chemicals, it very important to understand the type and magnitude of toxic pollutants, its fate in the environment and how it would transport from one matrix to another in the environment and exposure frequency and duration. Though, in real life, data is generally imperfect for various aspects which are very important for risk assessment. Most of the time, while assessing risk, scientist uses their own judgment and assumptions, which results into certain amount of uncertainty in the results. This is one of the reasons that while presenting risk assessments results, one should measure uncertainties and classify how consistent (or unreliable) the resulting risk assessments actually are.

Human Health Risk Assessment

A human health risk assessment method helps in estimating the type and likelihood of adversative health effects in humans who are exposed to toxic compounds in polluted environment, currently or in the future. Human health risk assessment includes four general steps, and is commonly conducted following various EPA guidance documents (Fig. 3.2) (EPA, 1992).

- *Problem identification* helps in identifying toxic chemicals which causes potential harm to human beings.
- *Dose-Response assessment* studies the mathematical relationship between exposure and effects.
- *Exposure assessment* helps in assessing the exposure of chemical in terms of frequency, duration of exposure and contact time with a stressor.
- *Risk characterization* assesses the type and magnitude of the risk caused from exposure of toxic chemicals/environmental pollutants.

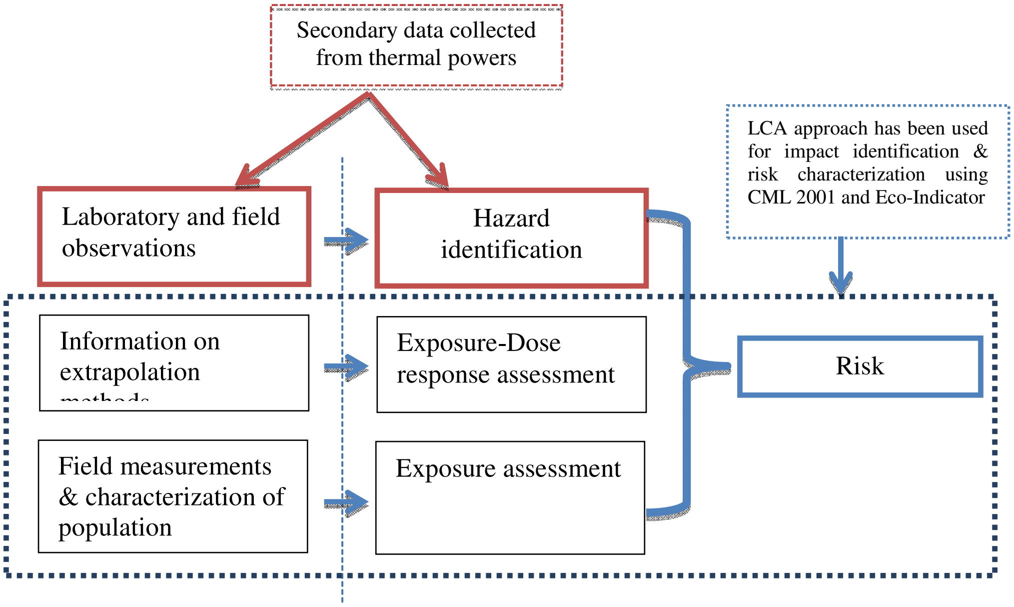


Fig. 3.2: Environmental risk assessment from thermal power plants

Ecological Risk Assessment

An ecological risk analysis is the method for measuring impacts of various chemicals/air emissions etc. on various species in ecosystem when they are exposed to these chemicals. Impacts magnitude is measured by assessing exposure frequency and duration of exposure to chemicals causing ecological impacts on various ecological species. Ecological risk analysis would be measured by using USEPA guidelines (U.S. EPA, 1998) as given below:

- Problem formulation – This step helps in identifying the type of plants or animals are under risk due to exposure of chemicals and how to protect them.
- Analysis – This step helps in measuring the exposure levels in various plants and animals, their frequency and duration of exposure. It also helps in assessing the probability of causing risk due to exposure of chemicals.

- Risk characterization – This step helps in measuring risk estimation and risk description. Risk estimation includes both exposure profiles and exposure-effects. Risk description helps in assessing the type of risk resulted due to exposure of chemicals and also assess the degree of detrimental effects on the ecosystem species.

3.3 LIFE CYCLE ASSESSMENT

The LCA is a structured, internationally standardized method and management tool for quantifying the emissions, resources consumed and environmental and health impacts that are associated with processes/services/technology (ISO 14040, 2006;14044, 2006).

There are various methods (e.g. environmental impact assessment (EIA), life cycle analysis etc.) used for assessment of environmental impacts from any project development or process. Most widely used method is EIA which is a regulatory mechanism for impact assessment but it has its specific limitations (Safer-environment, 2009 and Manuilova et al., 2008). The LCA method has been selected based on the following reasons for this study:

- The EIA is a regulatory framework for assessing impacts due to specific project, which is very general and specific to site and type of industry; whereas, LCA is having well defined methodology for assessing environmental impacts for life cycle of the project activities.
- In EIA, there are no specified/standardize methods for various environmental impacts assessment such as global warming, human toxicity, acidifications, and

difference is due to inconsistencies in the scope of assessment between EIA & LCA (Tukker, 2000).

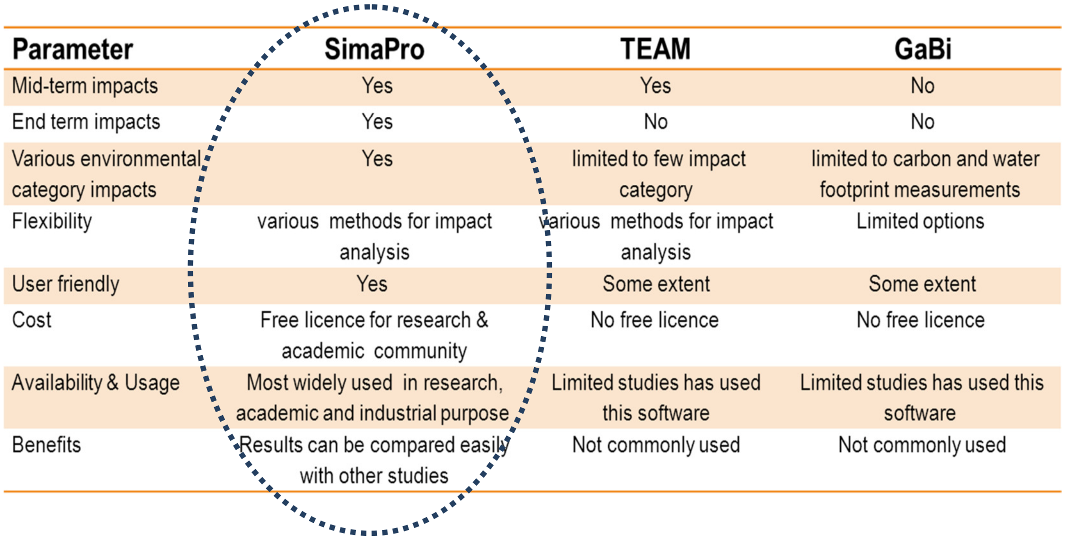
- The LCA approach assess the complete impacts during entire life cycle of a project or activities/process from global to local scale; whereas, EIA normally assess more limited impacts which as site specific and only negative in nature.

Aspects	**LCA**	**EIA**
Flexibility	Minimum	Flexible
Qualitative analysis	No	Yes
Quantitative analysis	Yes	Yes
Impact categorization	Standardized	Case by case
Impact locations	Primarily global & regional	Primarily local but variable
Standardization	International & custom variations	National and state

Based on above justifications, LCA approach has been used to assess the environmental impacts (on human health and ecosystem quality) of emissions (air, water and soil) from thermal power plants (imported coal and natural gas combined cycle based) as it provides the most reliable complete quantification of net environmental impact from a regional or global perspective (Hunt et al., 1974; Rosenbaum et al., 2008; Sonnemann et al., 2004). The LCA methodology used in this study follows the ISO 14040 and 14044 guidelines (ISO 14040, 2006 and ISO 14044, 2006). The broad framework of LCA methodology used is shown in Figure 3.3. It includes definition of goal and scope, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation of results.

Selection of SimaPro software for life cycle analysis

SimaPro has been selected for LCA in the current study based on literature survey. The comparison has been made between three software's i.e. SimaPro, TEAM and GaBi and it has been observed that SimaPro is better due to various factors as given below:



Parameter	SimaPro	TEAM	GaBi
Mid-term impacts	Yes	Yes	No
End term impacts	Yes	No	No
Various environmental category impacts	Yes	limited to few impact category	limited to carbon and water footprint measurements
Flexibility	various methods for impact analysis	various methods for impact analysis	Limited options
User friendly	Yes	Some extent	Some extent
Cost	Free licence for research & academic community	No free licence	No free licence
Availability & Usage	Most widely used in research, academic and industrial purpose	Limited studies has used this software	Limited studies has used this software
Benefits	Results can be compared easily with other studies	Not commonly used	Not commonly used

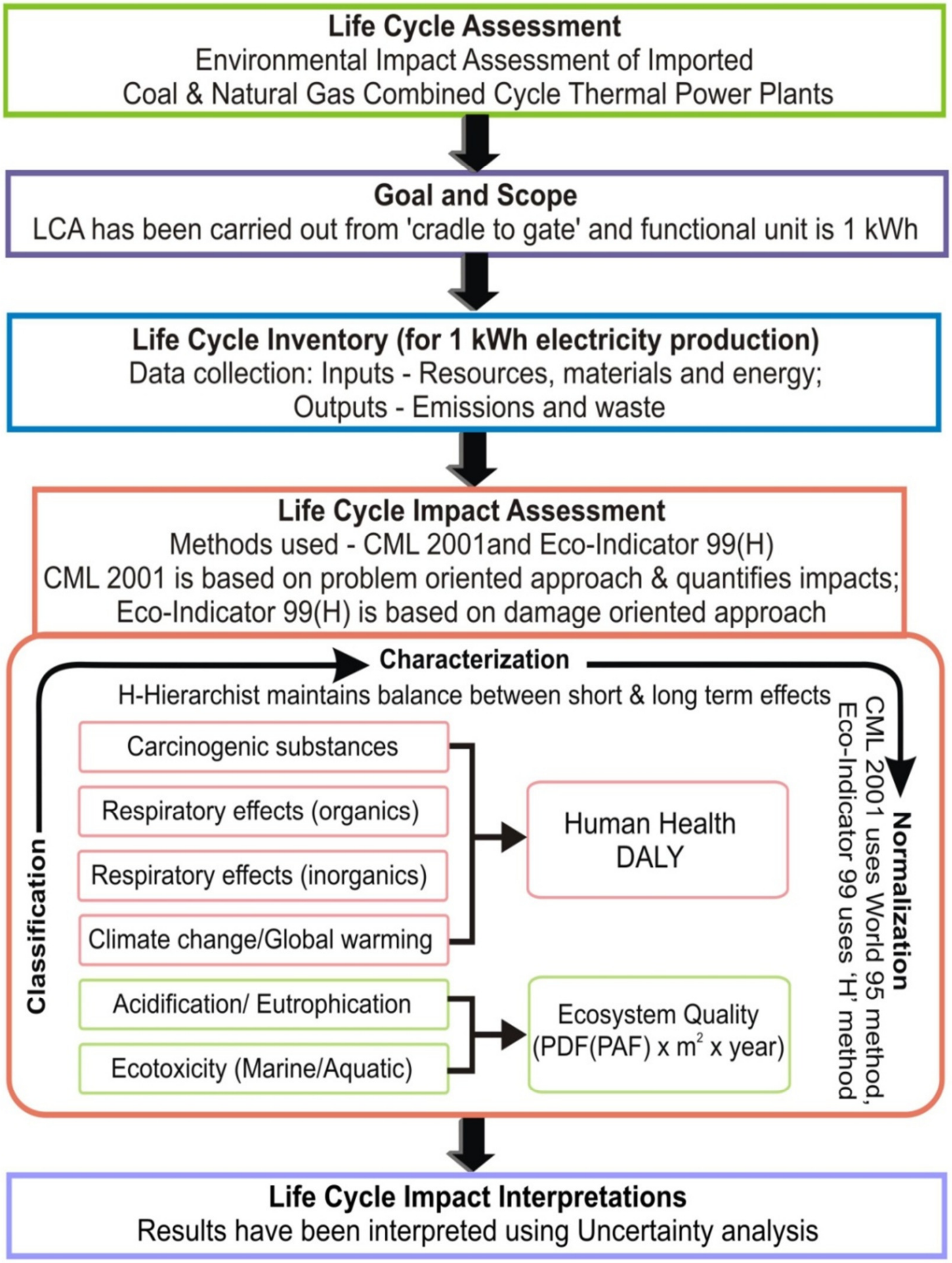


Figure 3.3: LCA framework used to estimate the environmental impacts from thermal power plants (imported coal and natural gas combined cycle)

3.3.1 SYSTEM BOUNDARY

Typically, LCA includes cradle to grave assessment of any technology or process. The boundary for any study is defined based on several factors such as time restriction, availability of funds and most importantly, availability of data for the research to be carried out. Based on the above factors, the system boundary for the current research is limited to the cradle to gate assessment for both thermal power plants (Figure 3.4 and 3.5). This study includes the processes taking place within the power plant boundary (i.e. electricity and water usage, combustion of imported coal/natural gas, wastewater disposal etc.) including upstream processes before power generation except transportation of natural gas/imported coal from the extraction/mining site to the power plant. The data for upstream processes such as natural gas extraction, purification and coal mining etc. have been adopted from the SimaPro database i.e. Eco-invent. The emissions from transportation of natural gas from KG basin to the plant site and coal transportation have not been included in the impact assessment due to non-availability of primary data from the plants.

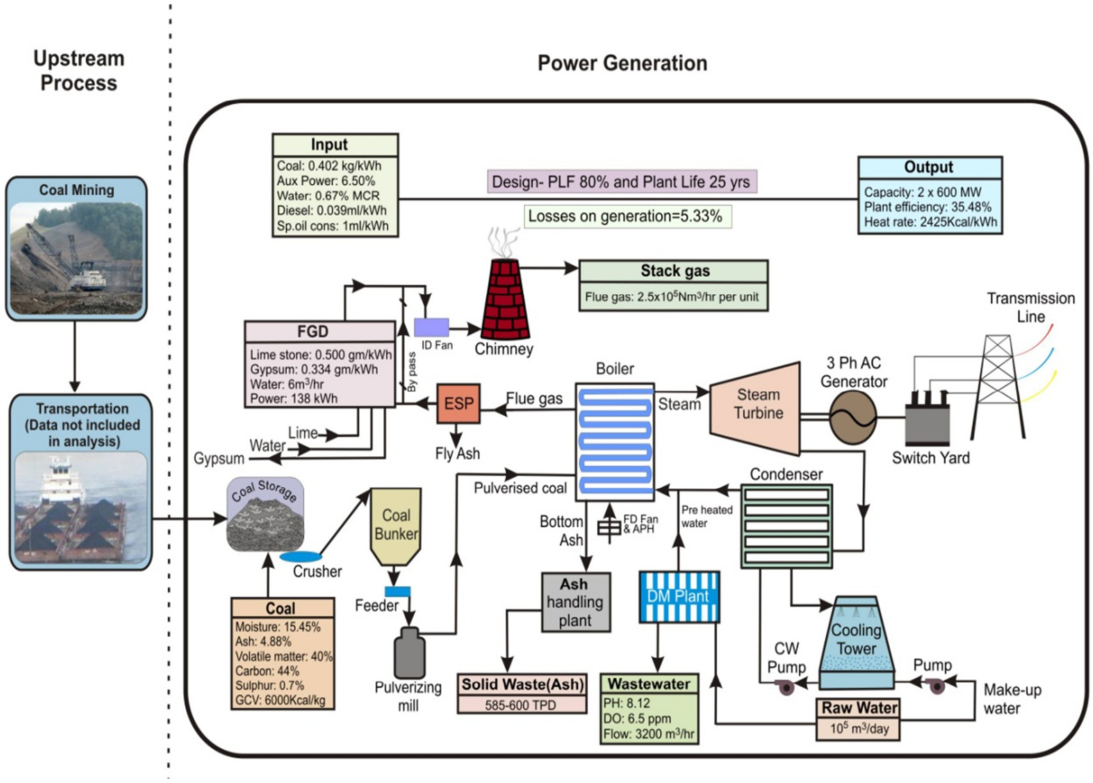


Figure 3.4: System boundaries of imported coal thermal power plant for life cycle assessment

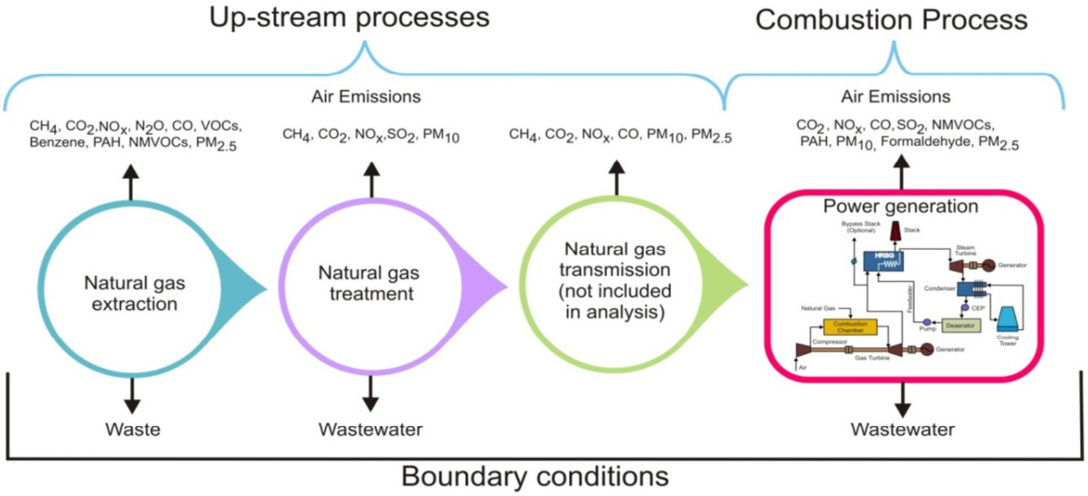


Figure 3.5: System boundaries of NGCC thermal power plant for life cycle assessment

3.3.2 FUNCTIONAL UNIT

The functional unit for the study is 1 kWh as net electricity generated from imported coal and natural gas combined cycle thermal power plants. All the inputs are normalised to the functional unit. However, other researchers have used similar functional unit and it would be easy to compare results with studies in this area at national and international levels

3.3.3 IMPACT ASSESSMENT METHODS AND IMPACTS CATEGORY

There are four steps in the life cycle impact assessment (LCIA) process, the first two of which are considered mandatory, while the last two are optional (ISO 14044, 2006).

- **Classification** - Classification involves assigning specific environmental impacts to each component of the LCI. It is here where decisions made during the scope and goal phase about what environmental impact categories are of interest come into play.
- **Characterization** - Once the impact categories have been identified, conversion factors – generally known as characterization or equivalency factors – use formulas to convert the LCI results into directly comparable impact indicators.
- **Normalization** - Some practitioners choose to normalize the impact assessment by scaling the data by a reference factor, such as the region's per capita environmental burden. This helps to clarify the relative impact of a substance in a given context. For instance, if global warming contributions are already high in the context in which the process is being assessed, a reference factor would normalize whatever the process global warming contributions are in order to clarify its relative impacts.

- **Weighting** – After normalization, weights would be assigned based on impacts for ranking the impact category.

This study was carried out using SimaPro software. The CML 2001 and Eco-Indicator 99 (H) methods have been used in this study for calculating environmental impacts as these are the most widely used midpoint and endpoint life cycle impact assessment methods, respectively (Ataei et al., 2012; Santoyo-Castelazo et al., 2011; PRé Consultants, 2010; Goedkoop and Spriensma, 2000).

The CML 2001 -This method is based on problem oriented approach (midpoint method) and quantifies various impacts. In this study, environmental impacts have been measured in terms of acidification, eutrophication, global warming and human toxicity potential.

The Eco-Indicator 99 (H) - This method is based on damage oriented approach (endpoint method) and gives results for various major impact categories. Hierarchist perspective (H) version of the Eco-Indicator 99 has been used in the current study to include long term perspective of the impacts and at the same time the damages are assumed to be avoidable by good management. In this study, environmental impacts due to carcinogens, respiratory organics, respiratory inorganics, climate change and acidification/ eutrophication have been measured.

Generally, the damage to human health is expressed in disability adjusted life years (DALY) that is an index used by the World Bank. It symbolizes the number of years of life lost due to premature mortality and the loss of years of productive life arising as a result of incapacity. The ecosystem quality damages are expressed in the possibly disappeared fraction of species in a specified area over a period of time (PDF.m^2.y) as a reason of the environmental load (acidification, eutrophication, land use and ecotoxicity). The harm caused to resources is usually expressed by the indicator surplus energy (to extract minerals or fossil fuels) as it is presumed that human beings will extract the best resources first and thereby abandoning the resources that are of inferior quality, for future extraction (Frischknecht et al., 2007).

Normalization - Normalization was done to bring all impact categories to the same units and to find out the relative contribution of each impact category to the normalized results. World normalization factor 1995 is used to normalize the impact categories in CML 2001 (Frischknecht et al., 2007a and Bösch et al., 2007).

Uncertainty analysis - SimaPro allows calculating uncertainty in inventory results using Monte Carlo analysis. A Monte Carlo analysis gives an indication of how reliable, complete and representative your results are. Each time, process iterates for hundred runs.

3.4 ECONOMIC ANALYSIS

Economic analysis in terms of LCC, which comprises, cost of plant design, installation, operation & maintenance, fuel cost, revenues from electricity generation, hidden damage cost (climate change and health damage) due to various pollutants released from thermal power plants. In this study, disposal cost for thermal power plants have not been included since environmental analysis was also carried out from cradle to gate only.

3.4.1 ESTIMATIONS OF PER UNIT GENERATION COST

The cost for 1 kWh electricity generation was calculated according to tariff notification for FY 2009-14 (CERC, 2009). The fixed cost of a power generating station was computed on annual basis, based on norms specified under these regulations[5], and recovered on monthly basis under capacity charge. The total capacity charge payable for a generating station shall be shared by its beneficiaries as per their respective percentage share / allocation in the capacity of the generating station. The procedure used for calculating cost of 1 kWh of electricity generation from both fuel types is shown in Figure 3.6. Cost components like fixed cost as well as variable cost has been calculated to estimate the per unit power generation cost for Coal and NGCC thermal power plants.

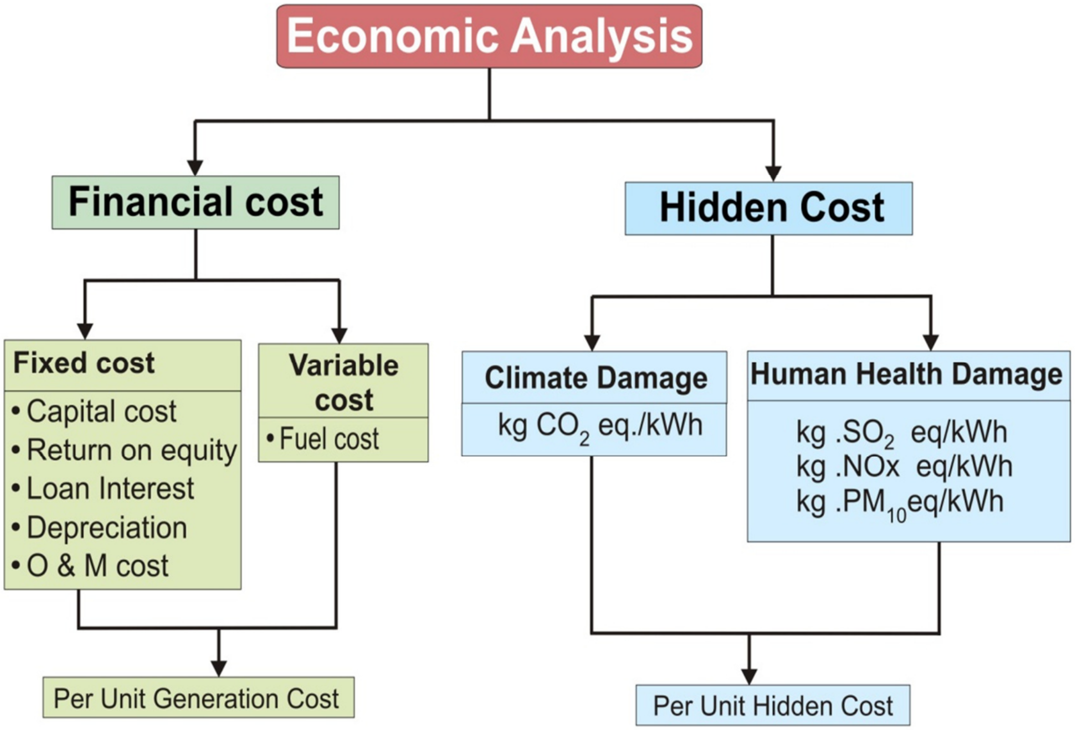


Figure 3.6: Economic analysis using life cycle costing for generation of 1kWh of electricity

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[5] Source: CERC (2009)

Sensitivity Analysis

While doing the economic analysis, for reporting single summary outcomes, such as cost of generation of 1 kWh of electricity, the interpretation of those results will largely depend on the level of confidence or uncertainty in various factors. This type of exercise would involve investigating the sensitivity of the model by changes in its inputs. In order to study the impact of changes in the input data, a sensitivity analysis has been carried out. Two variables have been included in sensitivity analysis i.e. fixed cost and variable cost.

3.4.2 ESTIMATION OF HIDDEN DAMAGE COST

Energy deficits, fuel security issues (both of coal and gas), rising prices of conventional energy sources and growing environmental concerns call for efficient utilization of the available energy resources. These indicate hidden costs of power generation that have indirect impact on humanity. The emissions from electricity generation result into various impacts on environment, human health and climate. Electricity generation results in various negative externalities like environmental degradation and impact on human health. Environmental and human health impacts can be measured in terms of mid-point and end-point impacts based on life cycle inventory data. In this study, inflation rate has not been considered and unit damage cost has been adopted from ExternE (2005) after conversion from Euro to Rupees[6].

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[6] Mid-Market rates: 2012-10-08 04:26 UTC (1 EUR= ` 67.773)

Climate Damage

The major global warming potential that comes from the power sector is due to CO_2 emission. For assessing and comparing the external effects with reference to each other and their costs, it is beneficial to convert them to a common unit. Therefore, this conversion of external effects into financial units results in external costs. The features associated with damage cost of the CO_2 emissions to a specific generation technology, in terms of per unit power generation are given by (ExternE, 2005; Wijaya and Limmeechokchai, 2010):

$$\begin{aligned}\boldsymbol{CO_2\ damage\ cost\ (Rs./kWh)}\\ &= \boldsymbol{CO_2\ emissions\ (kgCO_2\ eq./kWh)}\\ &\times \boldsymbol{Unitdamage\ cost\ (Rs./kgCO_2\ eq.)}\end{aligned}$$

The cost of unit damage is ` 1.287/kg CO_2 eq.

Health Damage

Health damage costs are generally region and site specific (ATSE, 2009), which are distinct from damage costs for CO_2 emissions. As these health impacts contribute to the largest part of the total cost, they are of utmost importance apart from costs related to global warming. Thus, a consensus has developed among public health experts that air pollution intensifies morbidity (especially cardiovascular and respiratory diseases) and results into premature mortality (ExternE, 2005), even at these current ambient levels. The main emissions considered to damage health are particulate material (PM_{10}), sulfur dioxide (SO_2) and nitrogen oxides (NOx).

Sulphur Dioxide Emissions

The combustion of coal results in SO_2 emissions (negligible in case of natural gas) during electricity generation. The SO_2 forms acid rain which further results into damage to ecosystem and human health such as difficulty in breathing, and even premature death. The SO_2 damage cost has been calculated by the following formulation (ExternE, 2005; Wijaya and Limmeechokchai, 2010):

$$\begin{aligned} &\boldsymbol{SO_2\ damage\ cost\ (Rs./kWh)} \\ &\qquad = \boldsymbol{SO_2\ emissions\ (kg\ SO_2\ /kWh)} \\ &\qquad \times \boldsymbol{Unitdamage\ cost\ (Rs./kg\ SO_2\ )} \end{aligned}$$

The cost of unit damage is ` 365/kg SO_2.

Nitrogen Oxides Emissions

The combustion of coal and natural gas results in NO_x emissions during electricity generation. When fuel is burnt at high temperatures, it results in the formation of NO_x. The NO_x forms acid rain and eutrophication which further results into damagee to ecosystem (impacts on species diversity, mainly to vascular plants and lower organisms) and human health (breathing and respiratory system diseases, lung tissue damage, and even premature death). The SO_2 damage cost has been calculated by the following formulation (ExternE, 2005; Wijaya and Limmeechokchai, 2010):

$$\begin{aligned} &\boldsymbol{NO_x\ damage\ cost\ (Rs./kWh)} \\ &\qquad = \boldsymbol{NO_x\ emissions\ (kg\ NO_x\ /kWh)} \\ &\qquad \times \boldsymbol{Unitdamage\ cost\ (Rs./kg\ NO_x)} \end{aligned}$$

The cost of unit damage is ` 284/kg NO_x.

The PM_{10} Emissions

The PM_{10} contains particles of size less than 10 µm. Fine and ultrafine particles are suspected to have a considerably stronger impact on human health than coarse particles (Honghong, Hao, Duan, Tang, Ning, & Xinghua, 2007). The PM_{10} affects the lungs, causes premature death of people with heart or lung disease, and leads to aggravated asthma. The PM_{10} damage cost has been calculated by the following formulation (ExternE, 2005; Wijaya and Limmeechokchai, 2010):

$$\begin{aligned} &\boldsymbol{PM_{10}\ damage\ cost\ (Rs./kWh)} \\ &\qquad = \boldsymbol{PM_{10}\ emissions\ (kgPM_{10}\ /kWh)} \\ &\qquad \times \boldsymbol{Unitdamage\ cost\ (Rs./kg\ PM_{10})} \end{aligned}$$

The cost of unit damage is ` 1694/kg PM_{10}.

CHAPTER 4 – DATA COLLECTION AND ANALYSIS

4.1 DATA COLLECTION

The secondary data has been collected from both thermal power plants using spread sheets. Data has been collected on two aspects for environmental (as provided in appendix A) as well as economic analysis as given below:

4.1.1 ENVIRONMENTAL DATA ANALYSIS

The raw secondary data has been collected for fuel composition; resources used and design parameters for both thermal power plants after pre-processing for usable form as an input in LCA analysis. Tables 4.1 to 4.6 presents' data taken from imported coal and NGCC thermal power plants.

Table 4.1: Imported coal composition

Proximate analysis		
Description	**Unit**	**Value**
Total moisture	%	15.45
Inherent Moisture	%	10.88
Ash Content	%	4.88
Volatile Matter	%	40
Fixed Carbon	%	43.98
Total Sulphur	%	0.7
Goss Calorific Value	kcal/kg	6000
Hard-grove Grindability Index	-	47
Size	mm	0-50mm

Table 4.2: Resources used and design parameters for imported coal thermal power plant

Parameters	**Measurements**
Specific Oil Consumption (LDO and HFO)	1 ml/ kWh
Station Heat Rate	2455 Kcal/ kWh
Losses on Generation	5.33 %
Diesel Consumption	0.039 ml/ kWh
Coal Consumption	0.402 kg/ kWh
Aux Power Consumption	6.5%
Water Consumption (% Maximum Capacity Rating)	0.67 %
Coal GCV	6000 Kcal/kg
Plant Capacity	1200 MW (2 units of 600 MW each)
Plant efficiency	35.48%
Life time	25 years
Plant load factor	85%
Fuel share (imported coal)	100%

Table 4.3: Resource consumption in CCNG thermal power plant for 1 kWh of electricity generation

Energy				**Resources**		
Electricity (kWh)	**Heat Rate** (kcal/kWh)	**Natural gas** (m^3)	**Natural gas CV** (kcal/SCM)	**Acid & Caustic** (gm)	**H2/N2/ Others** (kg or liters)	**Water** (litres)
0.03	2025	0.249	8200	0.032 & 0.025	-	0.75

Table 4.4: Natural gas composition

Natural Gas Composition	**Percentage (%)**
Methane	98.43
Ethane	0.44
Propane	0.19
i-Butane	0.0275
n-Butane	0.0275
i-Pentane	0.0275
n-Pentane	0.0275
Carbon dioxide	0.415
Nitrogen	0.415
Hydrogen	0

Table 4.5: Design parameters of CCNG thermal power plant

Design parameter	**Data**
Type of power plant	CCNG
Plant capacity	350 MW
Plant efficiency (net)	42%
Life time	25 years
Plant load factor	85%
Fuel share (NG)	100%

Table 4.6: Wastewater characteristics from imported coal thermal power plant

Wastewater Parameter			
pH	DO (ppm)	Temp (^{0}C)	Flow (m^3/hr)
8.12	6.5	33.74	3200

4.1.2 ECONOMIC DATA ANALYSIS

Economic analysis has been carried out using LCC approach. Secondary data has been collected for economic analysis using direct method as explained in chapter 3. The raw secondary data was pre-processed for usable form. Tables 4.7 and 4.8 provide input data used for estimation of per unit electricity generation cost from imported coal and NGCC thermal power plants, respectively.

Table 4.7: Input data for per unit electricity generation cost from imported coal thermal power plant[7]

S. No.	Particulars	Normative Parameters
1	Capacity of Plant	1200 MW
2	Capital Cost	3.84 Cr/MW
3	Debt Equity Ratio	70:30*
4	Return on Equity	15.5%*
5	Interest on Loan	14%
6	Working Capital (10% of Total Capital)	461.25Cr
7	Interest on working Capital	14%
8	Depreciation Rate	5.28%*
9	Operation and Maintenance cost	13.08Lakh/MW*
10	Plant Load Factor (PLF)	80%*
11	Plant Availability Factor	85%*
12	Specific Oil Consumption	1 ml/kWh
13	Price of Oil	37000/KL
14	Gross Calorific value of Oil	9500 KCal/litre
15	Station Heat Rate	2425 Kcal/kWh*
16	Cost of Coal	` 4800 / Tonnes

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[7] *Data as per CERC Tariff Regulations for FY 2009-14*

17	Auxiliary Power Consumption	6.5 %*
18	Plant Life	25 Years
19	Gross Calorific value of Coal	6000 Kcal/Kg.

Table 4.8: Input data for per unit electricity generation cost from NGCC thermal power plant[8]

S. No.	Particulars	Normative Parameters
1	Capacity of Plant	350 MW
2	Capital Cost	3.56 Cr/MW
3	Debt Equity Ratio	70:30*
4	Return on Equity	15.5%*
5	Interest on Loan	14%
6	Working Capital (10% of Total Capital)	124.8Cr
7	Interest on working Capital	14%
8	Depreciation Rate	5.28%*
9	Operation and Maintenance cost	16.54 Lakh/MW*
10	Plant Load Factor (PLF)	80%*
11	Plant Availability Factor	85%*
12	Station Heat Rate	2,045 Kcal/kWh*
13	Cost of Natural Gas	` 12 / SCM
14	Auxiliary Power Consumption	3%*
15	Plant Life	25 Years
16	Gross Calorific value of Gas	8200 Kcal/SCM.

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[8] *Data as per CERC Tariff Regulations for FY 2009-14*

Estimation of per Unit Generation Cost – Imported Coal Thermal Power Plant

The detailed methodology for estimating per unit generation has been explained in chapter 3.

A	**Plant Capacity (MW)**	1200
B	**Capital Cost Calculation**	INR
	Project Cost (Including IDC, Land & SD)	44000000000
	Initial Spares (2.5 % of CC)	1100000000
	Capital Cost per MW	37583333.33
	Total Capital Cost	45100000000
C	**Fixed Cost component Calculations**	
C.1	**Return on Equity**	
	Rate of Return	15.50%
	Debt	70%
	Equity	30%
	Equity Component	13530000000
	Debt component	31570000000
	ROE	2097150000
C.2	**Interest on Loan**	
	Rate of Interest	14%
	Interest on Debt	4419800000
C.3	**Interest on Working Capital**	
	Rate of Interest	14%
	Working Capital (10% of Capital)	4510000000
	Interest	631400000
C.4	**Depreciation**	
	Rate	5.28%
	Depreciation	2381280000

C.5	**O&M Cost**	
	Normative Rate (Lakh/MW)	13.08
	Cost for Installed Capacity	1569600000
	Total fixed cost per year (C.1+C.2+C.3+C.4+C.5)	11099230000
	PLF	80%
	PAF	85%
	Unit Generated Per Year	7148160000
	Fixed Cost/kWh	**1.55**
D	**Variable Cost Component Calculations**	
D.1	**Cost of Specific Oil consumption**	
	Specific Oil Consumption ml/kWh	1
	Cost of Oil/Ltr	37
	Cost of specific Oil Consumption/kWh	0.037
D.2	**Cost of Specific Lime Consumption**	
	Specific Lime Consumption kg/kWh	0.005
	Cost of Lime/kg	3
	Cost of specific Lime Consumption/kWh	0.015
D.3	**Heat contribution of Oil**	
	GCV of Oil Kcal/liter	9500
	Specific Oil Consumption	0.001
	Heat contribution of Oil Kcal/kWh	9.5
D.4	**Heat Contribution of Coal**	
	Station Heat rate	2425
	Heat Contribution of Oil	9.5
	Heat Contribution of Coal Kcal/kWh	2415.5
D.5	**Cost of Specific Coal Consumption**	
	Heat Contribution of Coal Kcal/kWh	2415.5

	GCV of Coal Kcal/Kg	6000
	Specific Coal Consumption kg/kWH	0.402583333
	Cost of Coal/Kg	4.8
	Cost of Specific Coal Consumption	1.9324
	Variable Cost Per Unit (D.1+D.2+D.5)	
	Variable Cost/kWh	1.9694
E	**Variable cost per unit at bus bar**	
	variable cost per unit	1.9694
	Auxiliary power consumption	6.50%
	Variable cost Ex-Bus/Unit	**2.106**
F	**Nominal Tariff/Unit (Fixed + Variable)**	**3.66**

Estimation of per Unit Generation Cost – NGCC Thermal Power Plant

B	**Capital Cost Calculation**	**INR**
	Project Cost (Including IDC, Land & SD)	12000000000
	Initial Spares (4.0 % of CC)	480000000
	Capital Cost per MW	35657142.86
	Total Capital Cost	12480000000
C	**Fixed Cost component Calculations**	
C.1	**Return on Equity**	
	Rate of Return	15.50%
	Debt	70%
	Equity	30%
	Equity Component	3744000000
	Debt component	8736000000
	ROE	580320000
C.2	**Interest on Loan**	
	Rate of Interest	14%

	Interest on Debt	1223040000
C.3	**Interest on Working Capital**	
	Rate of Interest	14%
	Working Capital (10% of Capital)	1248000000
	Interest	174720000
C.4	**Depreciation**	
	Rate	5.28%
	Depreciation	658944000
C.5	**O&M Cost**	
	Normative Rate (Lakh/MW)	16.54
	Cost for Installed Capacity	578900000
	Total fixed cost per year (C.1+C.2+C.3+C.4+C.5)	3215924000
	PLF	80%
	PAF	85%
	Unit Generated Per Year	2084880000
	Fixed Cost/kWh	**1.54**
D	**Variable Cost Component Calculations**	
D.1	**Cost of Specific Gas Consumption**	
	Station Heat Rate Kcal/kWh	2045
	GCV of Gas Kcal/SCM	8200
	Specific Gas Consumption SCM/kWh	0.249
	Cost of Gas/SCM	12
	Cost of Specific Gas Consumption	2.993
	Variable Cost/kWh	2.993
E	**Variable cost per unit at bus bar**	
	variable cost per unit	2.993
	Auxiliary power consumption	3%

	Variable cost Ex-Bus/Unit	**3.085**
F	**Nominal Tariff/Unit (Fixed + Variable)**	**4.63**

CHAPTER 5: RESULTS AND DISCUSION

5.1 ENVIRONMENTAL IMPACT ANALYSIS

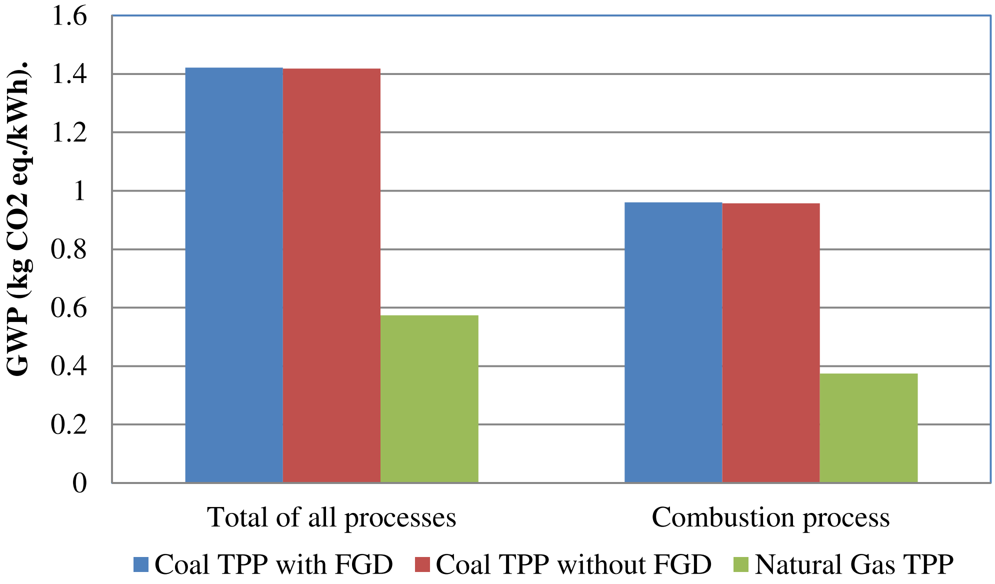
The LCA approach has been used for analysing environmental impacts due to imported coal and NGCC thermal power plants from cradle to gate. The environmental impact results have been summarized in appendix C.

5.1.1 GLOBAL WARMING AND CLIMATE CHANGE POTENTIAL

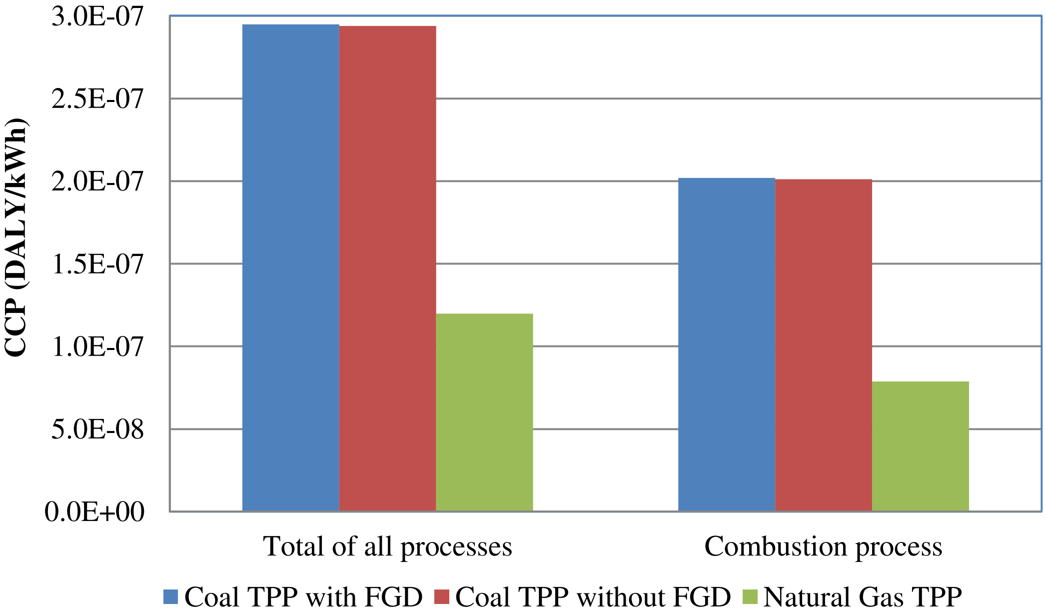
Figure 5.1 (a) and (b) presents the GWP and the CCP using CML 2001 and Eco-Indicator 99 (H) methods, respectively. CML 2001 measures GWP in kg CO_2 equivalents per kWh of electricity produced, while CCP in DALY (Disability Adjusted Life Years) per kWh of electricity produced. DALY is the number of disability years caused by exposure to toxic material multiplied by the “disability factor”, a number between 0 and 1 that describes severity of the damage (0 for being perfectly healthy and 1 for being fatal). Figure 5.1 (a) and (b) shows that total GWP (upstream and combustion processes) due to natural gas and imported coal thermal power plants from both the methods (CML 2001 and Eco-Indicator 99-H) are nearly 577 g CO_2 eq/kWh and 1122 g CO_2 eq/kWh, respectively; whereas, around 455 and 960 g CO_2 eq/kWh from combustion of natural gas and imported coal, respectively. It shows that imported coal has 1.95 times more global warming impacts from GHG emissions as compared to NGCC thermal power plant.

Similar results have been observed by Phumpradab et al. (2009) in Thailand from NGCC thermal power plant i.e. 539 g CO_2 eq/kWh electricity generation, whereas, from coal 1029 g CO_2 eq/kWh on an average in USA (Jaramillo et al., 2007). The small variations in results may be due to the difference in the capacity of power plants and station heat rate (SHR) (SHR is less in both the cases as compared to India, which is inversely proportional to the efficiency of thermal power plants).

In case of imported coal, the total (combustion + upstream processes) GWP and CCP (in terms of DALY) due to CO_2 emissions are 89.2%, due to CH_4 are 10.3% and less than 0.05% due to other substances such as CO and N_2O. However, in case of natural gas, 92% of the total climate change impacts and GWP are due to CO_2 emissions, 7% due to CH_4 and less than 0.05% due to other substances such as N_2O and CO. However, climate change impacts due to CO_2 emissions during combustion of imported coal are 99.7%, due to N_2O are 0.18% and less than 0.04% due to substance such CO and CH_4; whereas, in case of natural gas, more than 98% of the climate change impacts are a consequence of CO_2 emissions, nearly 1.8% due to CH_4 and insignificant amount due to N_2O as calculated from both methods.



(a) Global Warming Potential (CML 2001)



(b) Climate Change Potential (Eco-Indicator 99-H)

Figure 5.1: Global warming and climate change potential of 1 kWh electricity generated in imported coal and CCNG thermal power plants

There is no study available in Indian condition which can be compared with our results using life cycle approach for validation of current study results. Hence, results of this study have been compared with international studies (from Japan, USA, Mexico and Europe) for generation of 1 kWh of electricity. Table 5.1 compares the GHG emissions in terms of GWP impacts (g CO_2 eq/kWh of electricity generation) from imported coal and CCNG thermal power plants with our study. It has been observed that our results are in close agreement with studies carried out by various researchers in different countries (Hondo, 2005; Weisser, 2007; Jaramillo et al., 2007, Koornneef et al., 2008). All the results for GHG emissions have been compared for 1 kWh of electricity generation irrespective of plant capacity. The small variations in results may be due to the difference in the capacity of power plants, SHR, overall efficiency and the technology used in thermal power plants.

Table 5.1: Comparison of GHG emissions from coal and natural gas thermal power plants

References	Country	GWP (g CO_2 eq/kWh)			
		Imported Coal		Natural Gas	
		Combustion process	Total of all processes	Combustion process	Total of all processes
Current Study	India	960	1122	464.9	577.2
Hondo (2005)	Japan	886.8	975.2	407.5	518.8
Jaramillo et al. (2007)	USA	860-1050	910-1170	320-580	410-725
Weisser (2007)	Europe, North America and Japan	800-1000	950-1250	360-575	-
Koornneef et al. (2008)	Mexico	976	1092	473	-

5.1.2 HUMAN TOXICITY

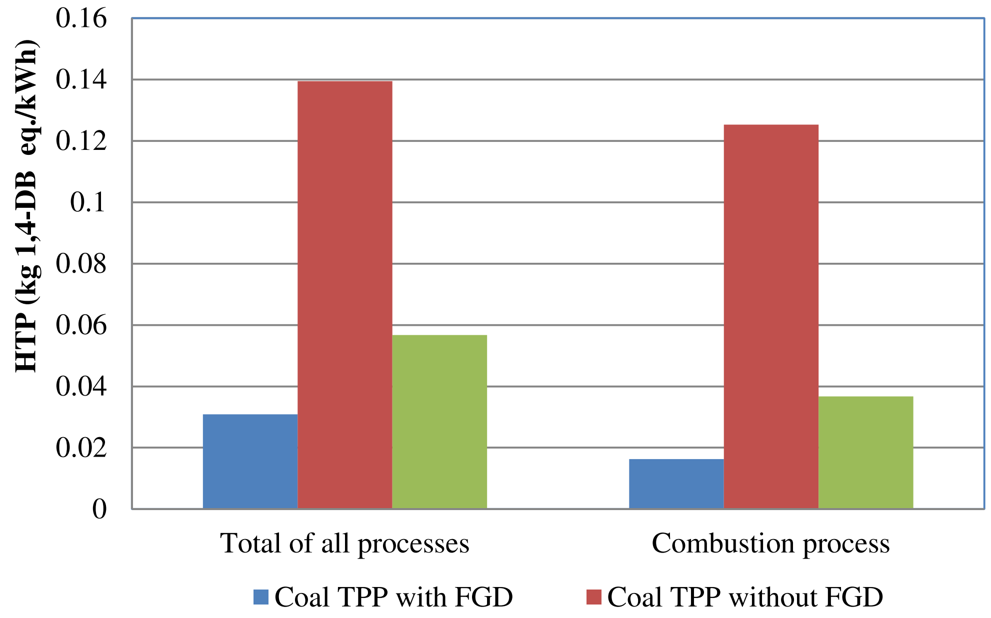
The human toxicity potential is expressed as kg 1,4-Dicholorobenzene (DB) equivalents per kWh of electricity produced using CML 2001 method, while carcinogen potential, respiratory inorganics and organics potential are measured as DALY per kWh of electricity produced using Eco-Indicator 99 (H) method.

Figure 5.2(a) shows that approximately 53%, 90% and 65% impacts as human toxicity potential (using CML 2001 method) are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. The major substances which contribute to human toxicity potential in case of imported coal are As, Cr (VI), Ni, Benzene, PAH and HF; whereas, in case of natural gas, 80% of the total human toxicity potential is due to polycyclic aromatic hydrocarbons (PAH) released into the atmosphere, nearly 18% due to benzene emissions and less than 0.2% from other substances.

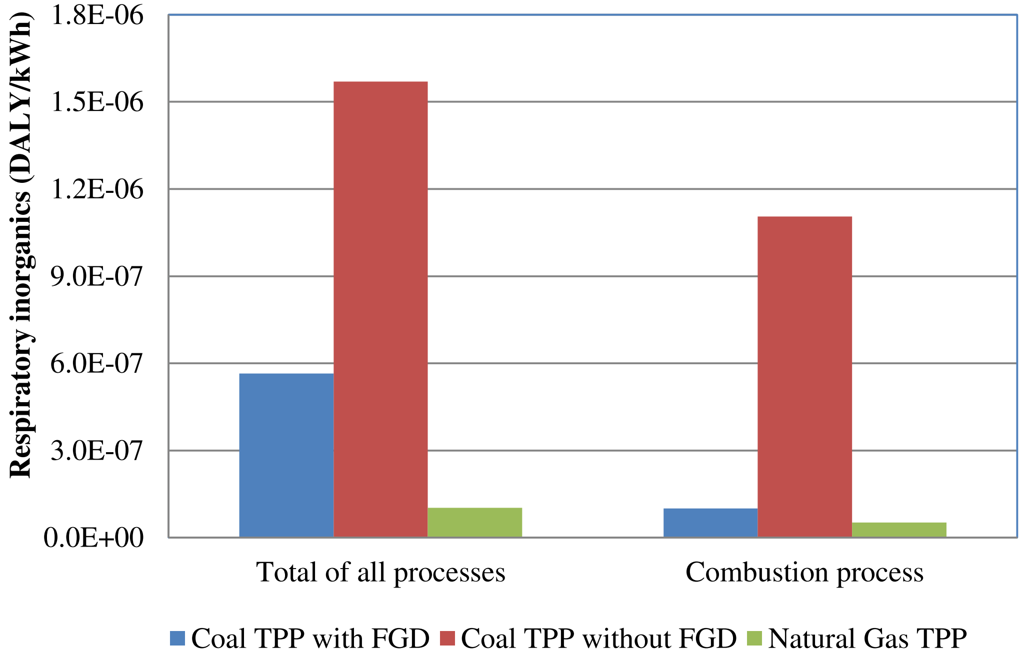
Figure 5.2(b) describes that approximately 18% (of 5.65E-07), 70 (of 1.57E-06), and 50% (of 1.03E-07) respiratory inorganic impacts are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall impacts due to respiratory inorganics in terms of DALY magnitude, combustion of imported coal in TPP without FGD results into approximately 2.8 times more impacts as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 0.82 times less impacts in terms of DALY as compared to imported coal with FGD technology. In case of combustion of imported coal, approximately 54.5% and 33% of the total respiratory inorganics impacts are caused by NO_x, about 19% and 27% by $PM_{2.5}$, nearly 26% and 38% by SO_2 and remaining 1.2% and 1.7% by other substances like PM_{10} and NH_3 respectively, with and without FGD technology. However, approximately 50% of the respiratory inorganics impacts are due to combustion of natural gas in power plant and remaining 50% are due to upstream processes. In combustion process, about 83.5% impacts are due to $PM_{2.5}$, about 16% from NO_x and less than 0.5% from other substances. Figure 5.2(c) describes that approximately 19% (of 1.73E-10), 19% (of 1.72E-10), and 12% (of 3.97932E-10) respiratory organics impacts are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall impacts due to respiratory organics in terms of DALY magnitude, combustion of natural gas in TPP results into approximately 2.3 times more impacts as compared to combustion of imported coal TPP. In case of imported coal, approximately 81% of the respiratory organics impacts are caused by upstream process and the remaining 19% are due to its combustion process in power plant in both cases i.e. with and without FGD; whereas, combustion of imported coal results in about 64% of the total respiratory organics impacts caused by xylene, nearly 14% by aliphatic unsaturated hydrocarbons and remaining 22% by other substances like toluene, benzene and formaldehyde in both cases, i.e. with and without FGD technology. However, approximately 88% of the respiratory organics impacts are caused by upstream process and the remaining 12% are due to combustion of natural gas in the power plant. Approximately 77% of total respiratory organics potential is caused by NMVOC, nearly 6% due to CH_4 and the remaining 17% due to other substances like ethane, formaldehyde, butane etc. In combustion process, about 48% impacts are due to NMVOC, nearly 38% from formaldehyde and about 14% from other substances.

Figure 5.2(d) describes that approximately 2% (of 1.11E-07), 7% (of 1.29E-07), and 19% (of 3.37E-09) carcinogens impacts are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall impacts due to carcinogens in terms of magnitude, combustion of imported coal in TPP without FGD results into approximately 1.2 times more impacts in terms of DALY as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 0.97 times less impacts in terms of DALY as compared to imported coal with FGD technology.

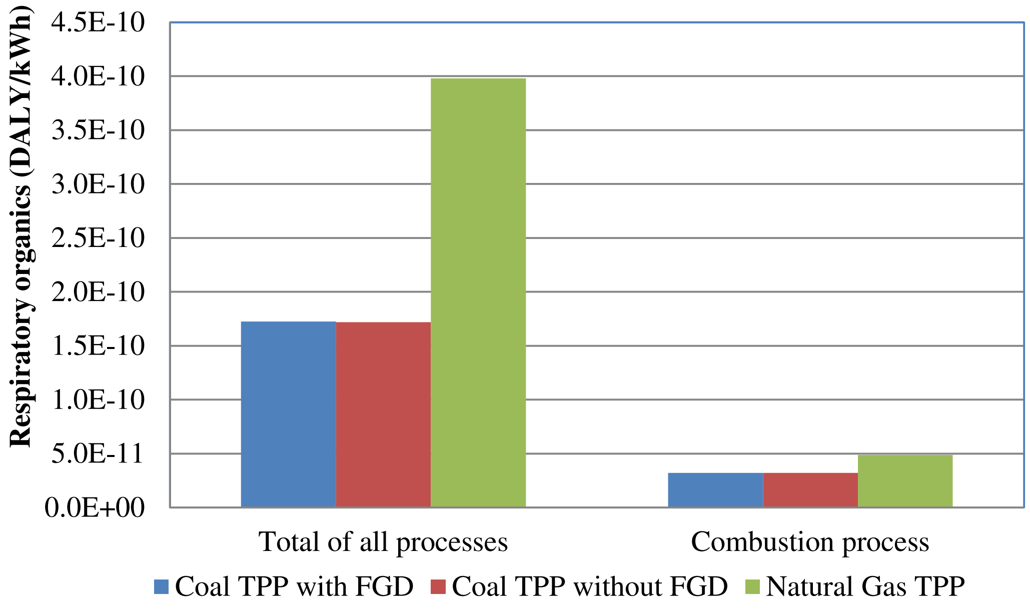
In case of combustion of imported coal, about 55% and 47% of the total carcinogens impacts are caused by $PM_{2.5}$, nearly 15% and 34% by As ions and remaining 30% and 19% are due to Cadmium and Cr (VI) respectively, in both cases i.e. with and without FGD technology. However, approximately 88% of the respiratory organics impacts are caused by upstream process and about 12% are due to combustion of natural gas in the power plant. Nearly 81% of the total carcinogens impact is due to upstream process and approximately 19% are caused by the combustion of natural gas in the power plant. Around 57% of the total carcinogens impact is due to arsenic ions released in the water, about 22% because of $PM_{2.5}$ released in the atmosphere and 21% from other substances like cadmium, benzo(α)pyrene etc. In combustion process, approximately 98% of the impacts are due to $PM_{2.5}$, nearly 1.5% from formaldehyde and less than 0.5% from other substances.



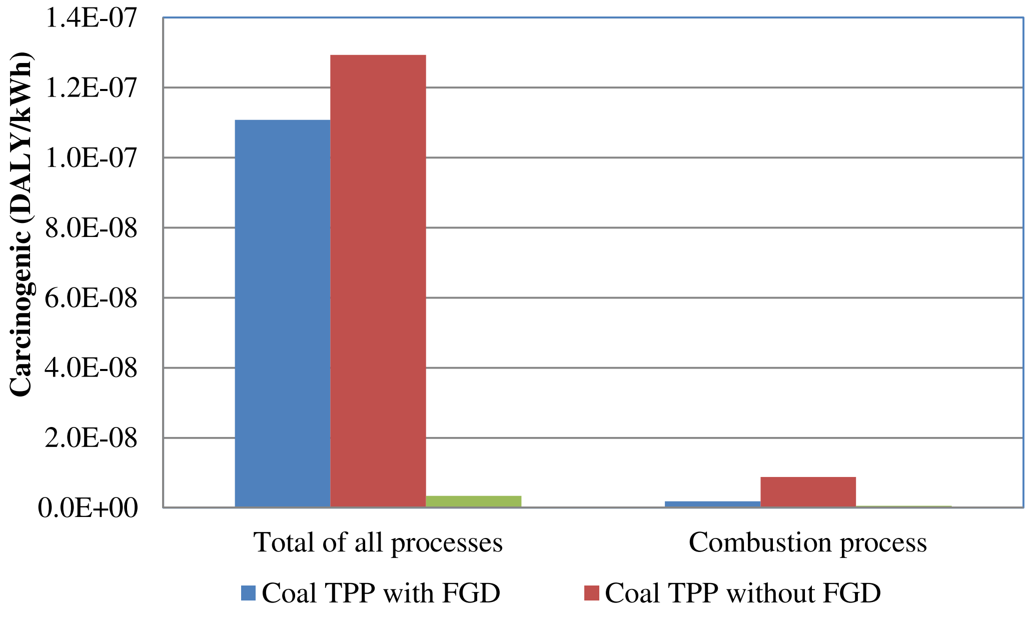
(a) Human Toxicity Impacts (CML 2001)



(b) Respiratory Inorganics Impacts (Eco-Indicator 99-H)



(c) Respiratory Organic Impacts (Eco-Indicator 99-H)



(d) Carcinogenic Impacts (Eco-Indicator99-H)

Figure 5.2: Human toxicity impacts of 1 kWh electricity generated in imported coal and CCNG TPPs

5.1.3 ACIDIFICATION AND EUTROPHICATION POTENTIAL

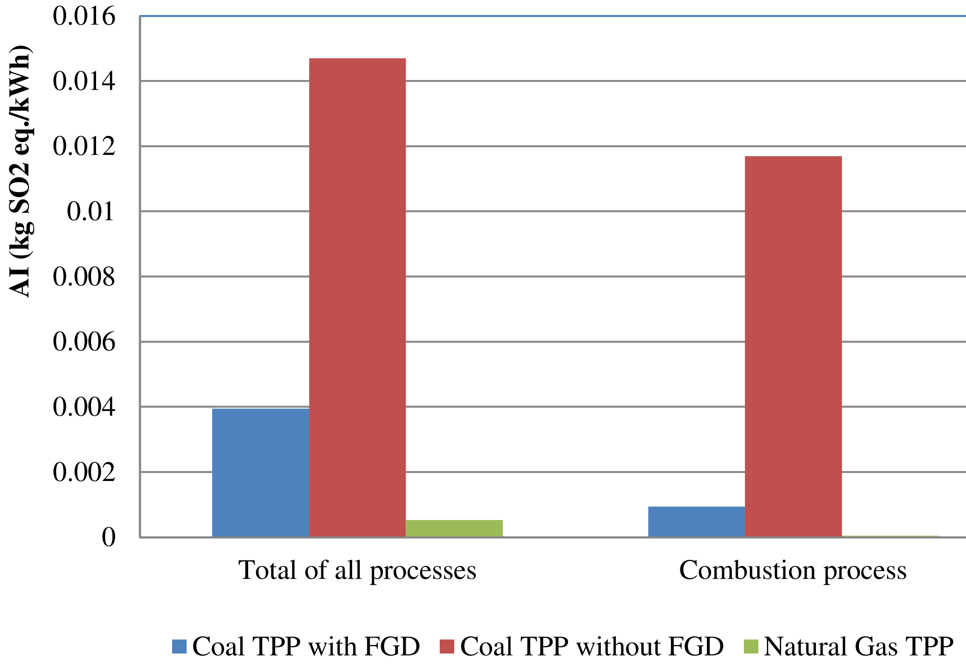
The acidification and eutrophication potential is measured in terms of kg SO_2 equivalents and kg PO_4 equivalents per kWh of electricity produced respectively using CML 2001 method, whereas, Eco-Indicator 99-H method explains the combined results of acidification and eutrophication potential in terms of Potentially Disappeared Fraction (PDF) per m^2 per kWh of electricity produced. Thus, PDF is a probability of the plants species to disappear from the area as a result of acidification and eutrophication. Since it is not possible to determine whether the damage is caused by changes in the nutrient level or by acidity, these two impact categories are combined.

Figure 5.3(a) shows that approximately 24% (of 0.004), 80% (of 0.015) and 10% (of 0.0005) of the acidification potential are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall acidification potential due to combustion of imported coal in TPP without FGD technology, it has approximately 3.7 times more acidification potential as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 0.87 times less potential as compared to imported coal with FGD technology. In case of combustion of imported coal, approximately 33% and 18% of total acidification potential is due to NO_x, nearly 60% and 80% is due to SO_2 and remaining 8% and 3% is due to other substances such as HCl and HF respectively, in both cases i.e. with and without FGD technology. However, in case of natural gas, nearly 63% of the total acidification impacts are due to SO_2, approximately 34% are due to NO_x

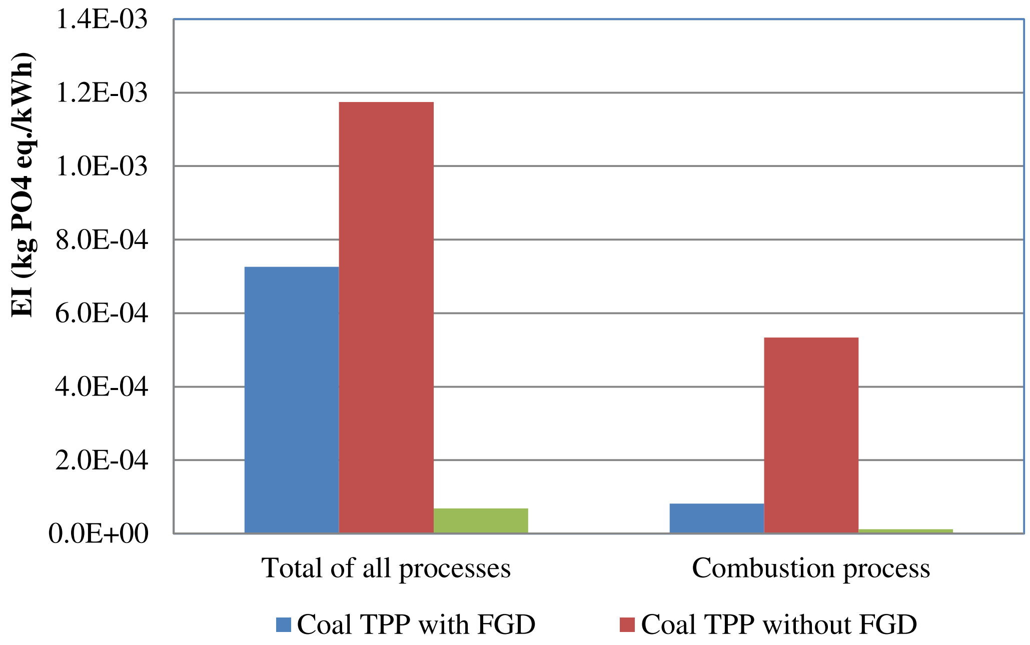
and 3% are a result of other substances. In combustion process, approximately 95% impacts arise due to NO_x and only about 5% from SO_2 and other substances.

Figure 5.3(b) shows that approximately 11% (of 0.00073), 45% (of 0.0012) and 18% (of 6.88 E-05) of the eutrophication potential are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall eutrophication potential due to combustion of imported coal in TPP without FGD technology, it has approximately 1.6 times more eutrophication potential as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 0.91 times less potential as compared to imported coal with FGD technology. In case of imported coal, about 18% and 49% by NO_x, nearly 79% and 49% by PO_4^{-3}, and 3% and 2% by NH_3, COD and NO^{-3} of total eutrophication potential respectively, with and without FGD technology; whereas, in combustion process, 100% eutrophication potential is due to NO_x in both cases. However, in case of natural gas power plant, approximately 67% of the total eutrophication impacts are due to NO_x emitted in the atmosphere, around 30% due to PO_4^{-3} released into the water and 3% because of other substances, whereas, in natural gas combustion process, the entire 100% impacts are due to NO_x.

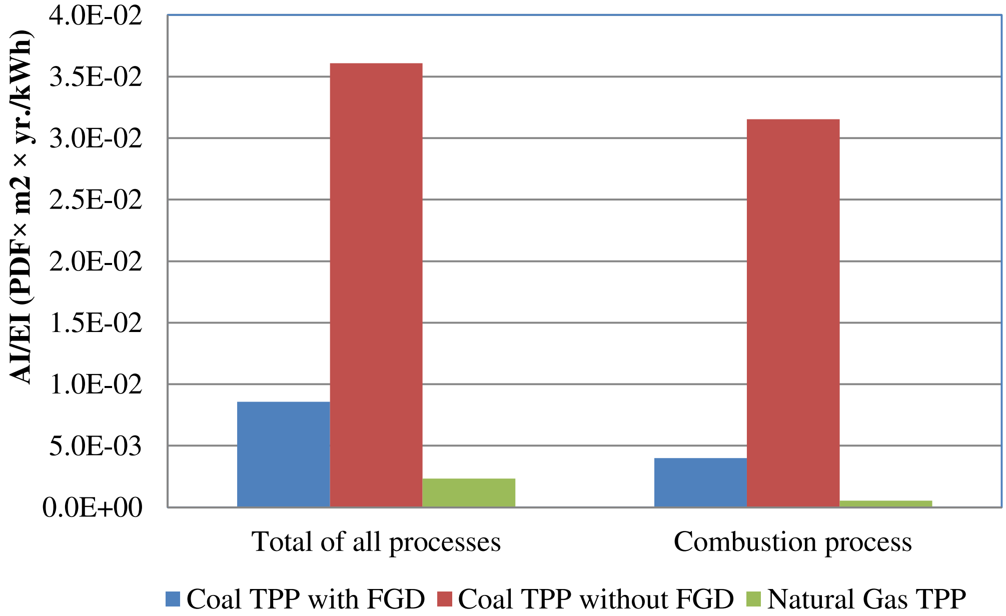
Figure 5.3(c) shows that approximately 47% (of 0.0086), 87% (of 0.0361) and 23% (of 0.0024) of the acidification/eutrophication impacts in terms of PDF are from combustion of imported coal with FGD, without FGD and natural gas respectively, and remaining are from all upstream processes. If we compare the overall acidification/eutrophication impacts in terms of PDF due to combustion of imported coal in TPP without FGD technology, it has approximately 4.21 times more impacts as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 0.73 times less impacts in terms of PDF as compared to imported coal with FGD technology. In case of imported coal, about 66% and 71% by NO_x, nearly 34% and 29% by SO_2, and 1% by NH_3 and SO^{-4} of overall impacts in terms of PDF respectively, with and without FGD technology; whereas, in case of natural gas power plant, approximately 90% of the total impacts are caused by NO_x, whereas, the remaining 10% are due to SO_2. However, in case of imported coal combustion process, 88% and 74% acidification/ eutrophication impacts are due to NO_x and remaining 12% and 26% are due to SO_2 respectively, in both cases i.e. with and without FGD.



(a) **Acidification Impacts (CML 2001)**



(b) Eutrophication Impacts (CML 2001)



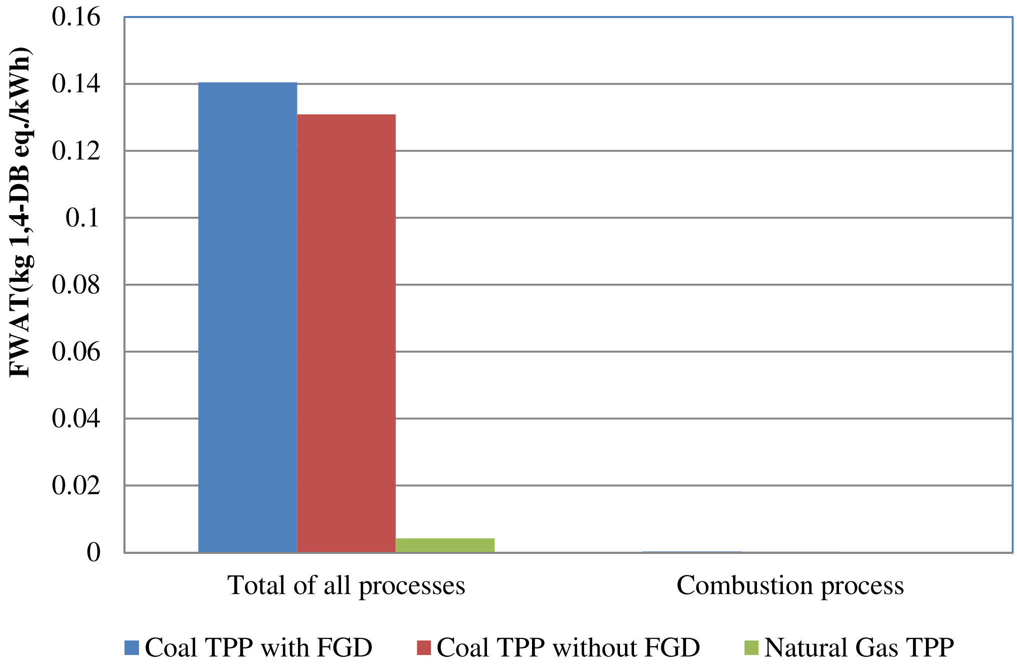
(c) Acidification/ Eutrophication Impacts (Eco-Indicator 99-H)

Figure 5.3: Acidification/Eutrophication potential and impacts of 1 kWh electricity generated in imported coal and CCNG TPPs

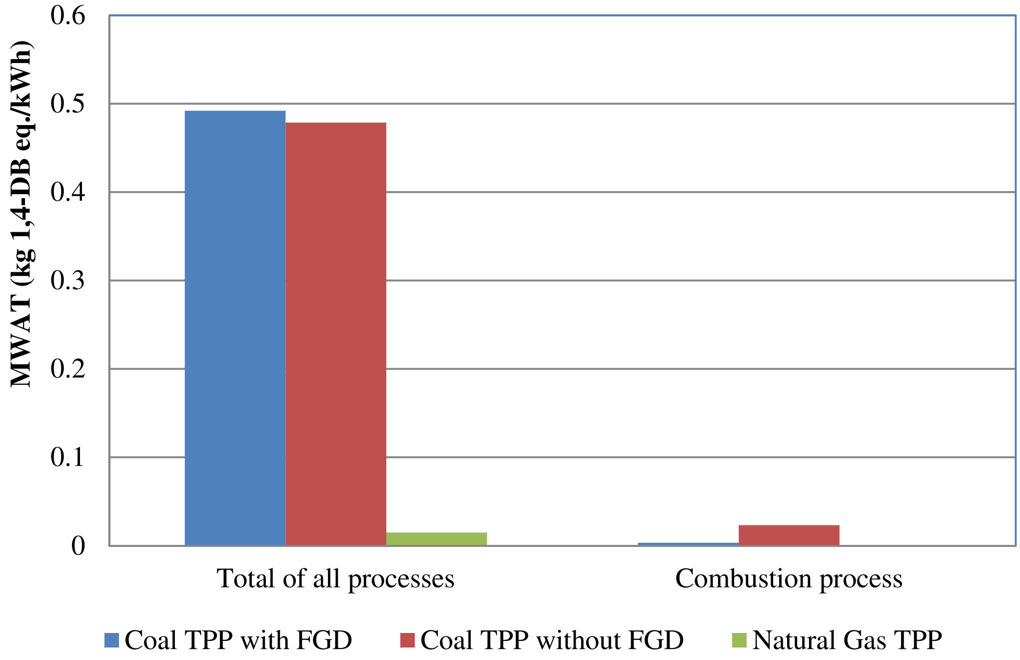
5.1.4 ECOTOXICITY (FRESH WATER AND MARINE WATER)

The fresh water and marine water potential is measured in terms of kg 1,4-DB equivalents per kWh of electricity produced using CML 2001 method, whereas, Eco-Indicator 99-H method explains the combined results of fresh water & marine water potential as ecotoxicity in terms of Potentially Affected Fraction (PAF×m^{2}×yr. per kWh of electricity produced. The ecotoxicity is characterized in PAF of species in relation to concentration of the toxic materials. The PAF is expressed as the percentage of species that are exposed to the toxic emissions. Higher the concentration, larger the number of species affected.

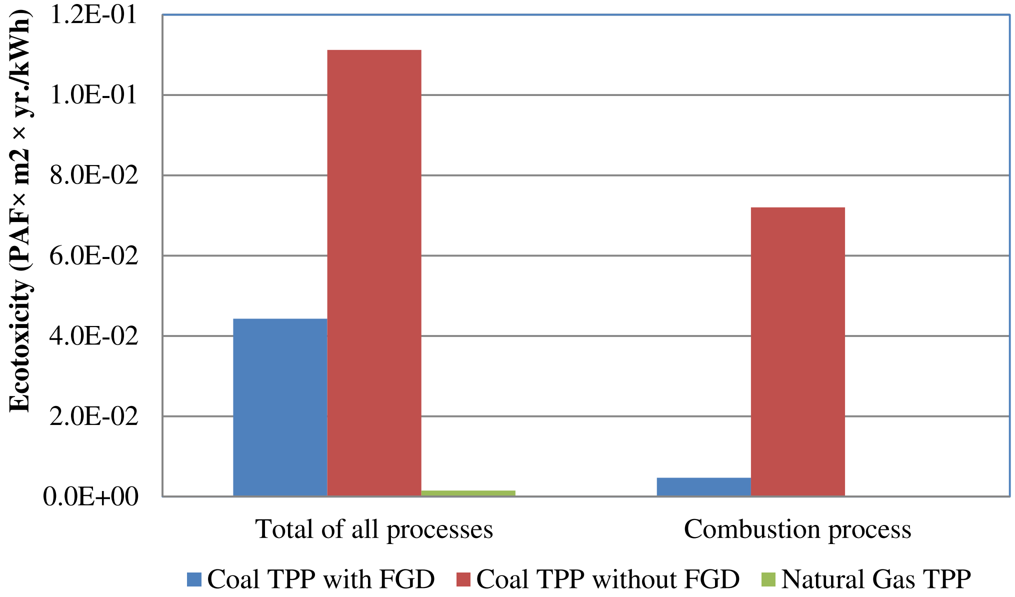
Figure 5.4 shows that combustion process in all three cases i.e. imported coal with FGD, without FGD technology and natural gas contributes less than 2% to ecotoxicity potential as well as impacts in terms of PAF as compared to all upstream processes. If we compare the overall ecotoxicity impacts in terms of PAF due to combustion of imported coal in TPP without FGD technology, it has approximately 1.7 times more impacts as compared to imported coal with FGD technology; whereas, combustion of natural gas in TPP has 3.5 times less impacts in terms of PAF as compared to imported coal with FGD technology. The overall impacts towards ecotoxicity are mainly a consequence of potential ions such as Ni, Cu, Cd, Cr, Zn, Co and V.



(a) Fresh Water Aquatic Toxicity Impacts (CML 2001)



(b) Marine Water Aquatic Toxicity Impacts (CML 2001)



(c) Ecotoxicity impacts (Eco-Indicator 99-H)

Figure 5.4: Ecotoxicity impacts of 1 kWh electricity generated in imported coal and CCNG TPPs

5.2 UNCERTAINTY ANALYSIS

5.2.1 IMPORTED COAL WITH FGD vs. WITHOUT FGD TECHNOLOGY

Uncertainty analysis (Monte Carlo analysis) of coal based power plant with FGD and without FGD technology has been carried out for 1 kWh of electricity generation for different parameters with Eco Indicator 99(H) method using confidence interval of 95%. Figure 5.5 shows that power plant with FGD is always a better option if ecosystem quality and human health are taken into consideration as compared to resources required to control emissions. With more than 99% certainty, it has been observed that the coal based power plant with FGD is a better choice as compared to coal based power plant without FGD for ecosystem and human health. It is obvious that if one more technology is incorporated into the existing system i.e. FGD technology, more resources may be required for operation and maintenance of this new technology as it is evident from the uncertainty analysis.

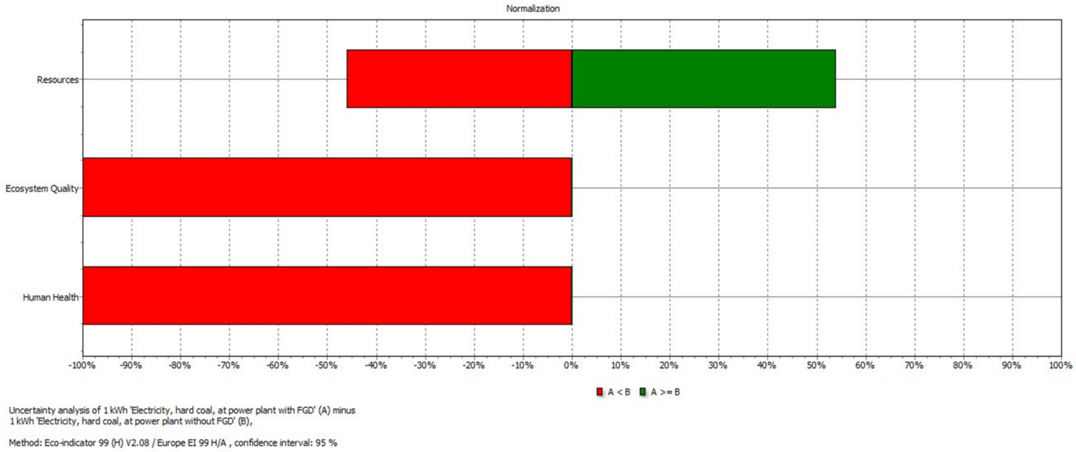


Figure 5.5: Uncertainty analysis for imported coal with FGD vs. without FGD technology

5.2.2 IMPORTED COAL WITH FGD TECHNOLOGY vs. NATURAL GAS

Uncertainty analysis (Monte Carlo analysis) of coal based power plant with FGD and natural gas has also been carried out for 1 kWh of electricity generation for different parameters with Eco Indicator 99-H/A method using confidence interval of 95%. Figure 5.6 shows that natural gas based power plant may prove to be a better choice if ecosystem quality and human health are taken into consideration (with >99% certainty). It can be inferred from the uncertainty analysis that if resources are taken into account, then coal based power plant with FGD consumes much less resources as compared to the natural gas based power plant (>99% certainty) if one has to consider processes from cradle to gate.

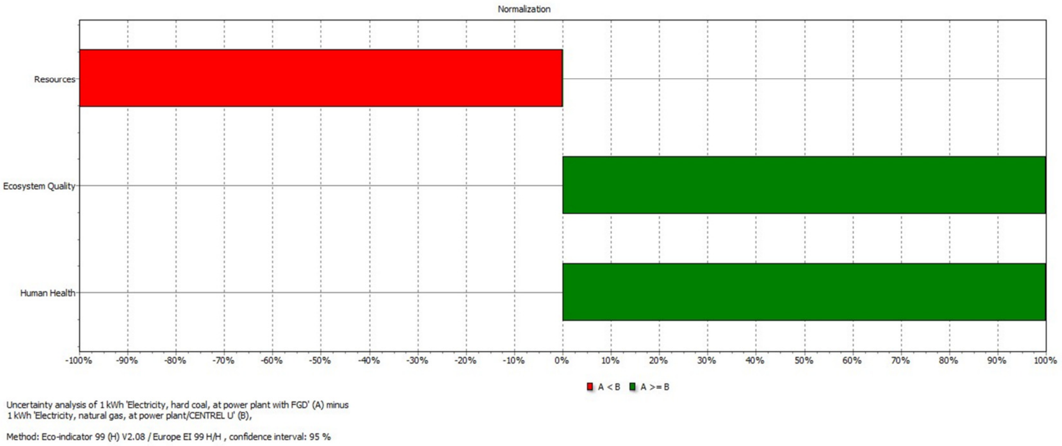


Figure 5.6: Uncertainty analysis for imported coal with FGD vs. natural gas

5.3 ECONOMIC ANALYSIS

Economic analysis for both thermal power plants has been carried out which includes cost comparison for electricity generation and hidden damage cost (climate change and health damage) due to various pollutants released from thermal power plants.

5.3.1 ELECTRICITY GENERATION COST

The cost of electricity generation from power plants has been divided into fixed and variable costs (Figure 3.6). Fixed costs include capital costs. Variable costs include fuel (imported coal and natural gas) and variable operation & maintenance costs. The estimation of fixed costs per unit of electricity generation requires estimation of factors such as the life of power plant, plant load factor (PLF), and discount rate. Variable cost requires estimation of fuel cost, heat rate, fuel heat content and the discount rate. Per unit generation cost from imported coal and natural gas based thermal power plants are ` 3.66 and 4.63 respectively (Table 5.2).

Table 5.2: Per unit generation cost of electricity from imported coal and NGCC thermal power plants

Parameter	Units	Coal based TPP	Gas based TPP
Fixed Cost	Rs/kWh	1.55	1.54
Variable Cost	Rs/kWh	2.11	3.09
Total Cost	Rs/kWh	3.66	4.63

The data used for calculation of unit generation cost is provided in Tables 4.7-4.8 and detailed process for estimating cost has been provided in section 4.1.2. In order to study the impact of changes in the input data, a sensitivity analysis has been carried out. It reveals that the increase in cost due to installation of FGD system in coal thermal power plant is quite clear (Xu, 2010). The electricity generated from coal thermal power plant less sensitive due to changes in fuel price; whereas, in case of natural gas, per unit generation cost is more sensitive due to change in natural gas price (Figure 5.7).

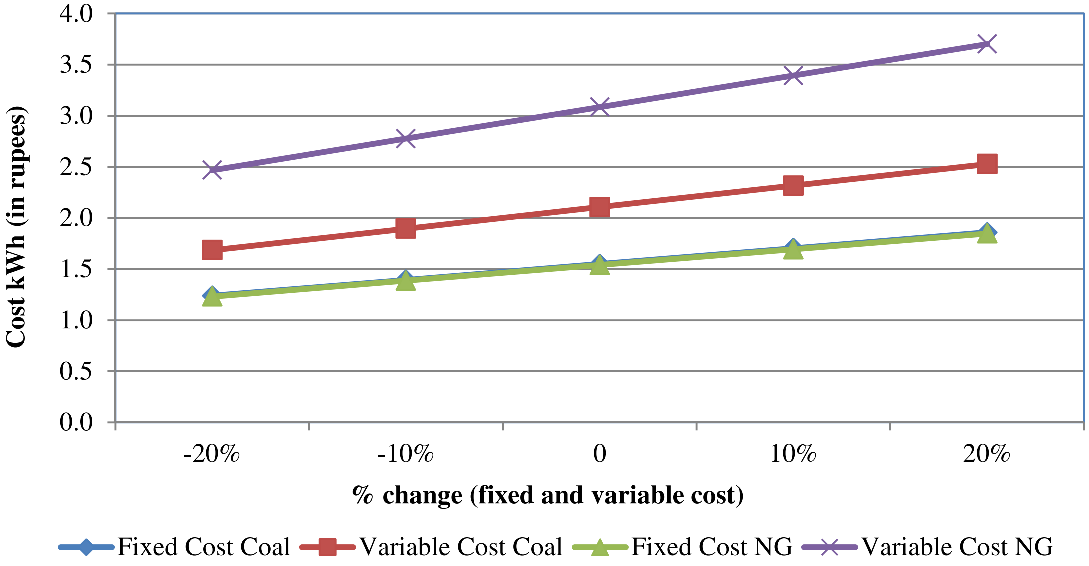


Figure 5.7: Impact of fixed and variable cost on per unit electricity generation cost

5.3.2 HIDDEN COST

Electricity generation results in various negative externalities like environmental degradation and impact on human health (Cropper et al., 2012). Hidden cost has been estimated for climate damage and human health damage. Climate damage cost has been estimated due to global warming potential in terms of CO_2 eq. per kWh electricity generation using LCA analysis as described in section 5.1 (Table 5.3).

Table 5.3: Climate damage cost

Power Plant	kg CO_2 eq./kWh	Unit damage cost (Rs/kg)	Damage cost (Rs/kWh)
Coal Fired	0.96	1.287	1.24
NGCC	0.465	1.287	0.60

Human health damage has been estimated due to SO_2, NO_x and PM_{10}. The health damage has major impact on external costs. The values of unit health damage taken in the current study are ` 365/kg, ` 284/kg, and ` 1694/kg for $SO_2$, $NO_x$, and $PM_{10}$ emissions, respectively (Widiyanto et. al., 2003). The calculated total health damage cost (for all three pollutants i.e. $SO_2$, $NO_x$, and $PM_{10}$) from imported coal based thermal power plant is ` 4.89/kWh and for NGCC thermal power plant, it is ` 0.58/kWh. Table 5.4 shows the calculated values of health damage costs.

Table 5.4: Calculated health damage costs from imported coal and NGCC thermal power plants

Power Plant	**SO_2 damage (Rs/kWh)**	**NO_x damage (Rs/kWh)**	**PM_{10} damage (Rs/kWh)**	**Total health damage cost (Rs/kWh)**
Coal Fired	2.73	1.10	1.05	4.89
NGCC	0.00	0.58	0.00	0.58

The hidden cost estimated from climate and health damage is ` 6.12/kWh and ` 1.18/kWh from coal and NGCC thermal power plants, respectively (Table 5.5).

Table 5.5: Hidden damage costs from imported coal and NGCC thermal power plants

Power Plant	**Health damage cost (Rs/kWh)**	**Climate damage cost (Rs/kWh)**	**Hidden damage cost (Rs/kWh)**
Coal Fired	4.89	1.24	6.12
NGCC	0.58	0.60	1.18

The decision making process for the selection of technology should also include the cost to environment and human health. The annexation of environmental externalities in the final energy costs encourages technological innovations in power sector (Kammen and Pacca, 2004). Policies to control air pollution from Indian power plants have traditionally focused on reducing particulate emissions, due to the high ash content of Indian coal. The low sulfur content of Indian coal has, perhaps, been responsible for failure to directly control SO_2 emissions (Chikkatur and Sagar 2007). It is important to evaluate the environmental and human health damage associated with power generation to mitigate the impacts of externalities by utilizing life-cycle and other more integrative methods for economic analysis. This would bridge the gap between engineering and financial assessments of the prices of energy services, and the wider social and environmental benefits, as well as costs of power generation from various alternative technology options. Therefore, this study suggests that more emphasis should be placed on direct SO_2 controls as well as NO_x and CO_2 emission to reduce the hidden (damage to climate and human health) cost from power generation process. This study analyses the health damages associated with power plants which can be used to evaluate the benefits of various alternative power generation technologies such as FGD, CCS, IGCC, SC and NGCC (Table 5.6).

Table 5.6: Emission reduction and hidden cost from alternative power generation technologies

S. No.	Technology	Technology cost/kWh	Emission reduction (%)			
			CO_2	SO_2	NO_x	PM_{10}
1	PC - Imported coal	3.66	0	0	0	0
2	PC + FGD	3.80	0	95	80	25
3	PC + CCS [a]	4.20	90	NR	NR	NR
4	PC + CCS + FGD	4.34	90	95	80	25
5	IGCC [a, b]	5.28	35	96	91	86
6	SC [a, b]	3.78	30	20	20	20
7	NGCC	4.63	52	90	47	90
			Hidden cost (₹/kWh)			
S. No.	**Technology**	**Technology cost/kWh**	**CO_2**	**SO_2**	**NO_x**	**PM_{10}**
1	PC - Imported coal	3.66	1.24	2.73	1.10	1.05
2	PC + FGD	3.80	1.24	0.14	0.22	0.79
3	PC + CCS	4.20	0.12	2.73	1.10	1.05
4	PC + CCS + FGD	4.34	0.12	0.14	0.22	0.79
5	IGCC	5.28	0.81	0.11	0.10	0.15
6	SC	3.78	0.87	2.18	0.88	0.84
7	NGCC	4.63	0.60	0.00	0.58	0.00

Note: Emission reduction from various alternative technologies have been taken from - [a]Singh et al., 2011; [b]IEA ETSAP (2010) and technology cost has been taken from - [b]IEA ETSAP (2010);

Figure 5.8 shows that total cost (technology and hidden costs) for electricity generation from imported coal thermal power plant is ₹ 9.78/kWh in which, about 63% is due to hidden cost. The installation of FGD technology in imported coal thermal power plant (PC + FGD) results into reduction of hidden cost by 61% with an incremental cost of ₹ 0.14/kWh. Further, installation of CCS technology in imported coal thermal power plant (PC + CCS) results into reduction of hidden cost due to CO_2 by 18% with an incremental cost of ₹ 0.54/kWh; whereas, installation of FGD and CCS technology together in imported coal thermal power plant (PC + FGD + CCS) results into reduction of hidden cost by 79% with an incremental cost of ` 0.68/kWh. However, IGCC, SC and NGCC thermal power plants results into reduction of hidden cost by 81%, 22% and 81% with an incremental cost of ` 1.62/kWh, ` 0.12/kWh, ` 0.97/kWh, respectively, in comparison to PC.

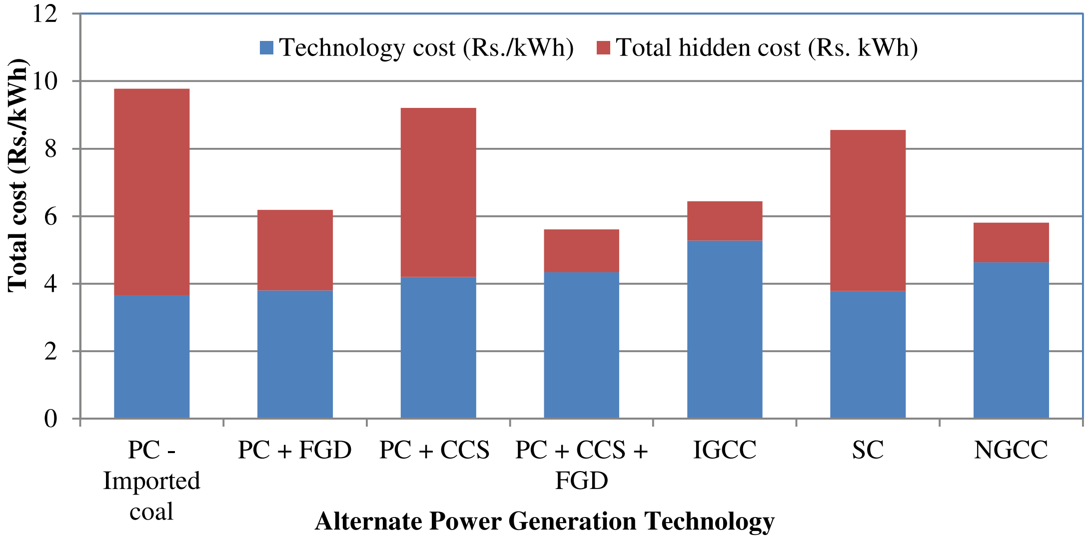


Figure 5.8: Total cost (technology and hidden cost) per unit electricity generation from alternative technologies

In view of alternative technology assessment based on economic analysis, it appears that IGCC and NGCC are better technologies in terms of cost reduction by 81% for environmental and health damages by adding extra cost of ` 1.62/kWh and ` 0.97/kWh, respectively, in comparison to PC. However, IGCC plants are very few in operation in the world and feasibility of IGCC plants would depend significantly on the overcoming of the technology risk. In case of NGCC, the availability of natural gas is limited due to more demand from transport and domestic sector. After this, second choice is PC + CCS + FGD, but CCS technology has its own limitations (Singh et al., 2011). Third choice is PC + FGD, which is a better choice for reducing health damages (61% in comparison to PC) from SO_2, NO_x and PM_{10} by additional cost of ` 0.14/kWh.

5.4 SUMMARY

The summarized result of environmental impacts from imported coal (with and without FGD) and NGCC thermal power plants is presented in Table 5.7.

Table 5.7: Critical assessment of environmental impacts for imported coal (with and without FGD) and NGCC thermal power plants

S. No.	Impact category	Percent reduction in impacts with FGD from coal thermal power plant	Emissions from coal TPP with FGD system in comparison with natural gas
01	Global warming potential	No change	Natural gas emissions are approximately 1.9 times less
02	Acidification potential	93 %	Natural gas emissions are 7.5 times less
03	Eutrophication potential	88 %	Natural gas emissions are 6.66 times less
04	Ecotoxicity potential	93 %	Natural gas emissions are 28 times less
05	Human toxicity	88 %	Natural gas emissions are 2.5 times more

The summarized result of economic analysis including per unit electricity generation cost as well as per unit hidden cost from imported coal, NGCC and alternative power generation technologies is presented in Table 5.8.

Table 5.8: Critical assessment of economic impacts for various alternative technologies used in power generation

S. No.	Technology	Technology cost/kWh	Hidden cost (` /kWh)
1	PC - Imported coal	3.66	6.12
2	PC + FGD	3.80	2.38
3	PC + CCS	4.20	5.00
4	PC + CCS + FGD	4.34	1.27
5	IGCC	5.28	1.16
6	SC	3.78	4.77
7	NGCC	4.63	1.18

CHAPTER 6: CONCLUSIONS

The LCA approach has been used in this study for measuring environmental impacts of imported coal (with and without FGD system) and NGCC thermal power plants using CML 2001 and Eco-Indicator 99-H methods in India.

6.1 CONCLUSIONS

The study reveals that imported coal has approximately 1.9 times more impacts as compared to natural gas in terms of GWP and CCP due to various emissions such as CO_2, CH_4 and N_2O. It has also been observed that electricity generation using natural gas is a good substitute in terms of GHG emissions as compared to coal and oil in developing countries like India. In case of acidification potential, NGCC thermal power plants contributes only 3% and 20% impacts as compare to imported coal thermal power plant with and without FGD technology, respectively. The NGCC thermal power plant causes only 6% of eutrophication problem as compare to imported coal thermal power plant. Imported coal thermal power plant has almost double human health impact as compare to NGCC thermal power plant based on CML 2001 midpoint impact. In overall, NGCC is better option as compare to imported coal thermal power plant in terms of overall impacts on human health and ecosystem quality with both methods CML 2001 and Eco-indicator 99(H) methods. However, if we compare impacts using endpoint method (Eco-indicator-

99-H), then NGCC thermal power plant causes only 3% and 10 % damage on ecosystem quality as well as human health in comparison to imported coal thermal power plants, respectively.

Economic analysis discussed in chapter 5 shows that IGCC and NGCC are superior technologies in terms of cost reduction due to negative environmental externalities by 81% with an additional cost of ` 1.62/kWh and ` 0.97/kWh, respectively, in comparison to PC. Second choice would be PC + CCS + FGD, but CCS technology has its own limitations due to increase in human health and eutrophication potential. Third option is PC + FGD, which is a better choice for reducing health damages by 61% in comparison to PC due to SO_2, NO_x and PM_{10} with an additional cost of ` 0.14/kWh. It is important to note that additional cost implication of ` 0.14/kWh due to installation of FGD technology results into reduction of 61% hidden damage cost, which is a very good option in terms of socio-economic cost-benefits in Indian scenario.

6.2 RECOMMENDATIONS

This study reveals that certainly natural gas is a better option in terms of overall environmental aspects as compared to imported coal without implementation of clean coal technologies. It emerged from this study that by installation of FGD technology in Indian condition results into reduction of very significant environmental and health impacts. In case of imported coal, sulphur content is high; therefore, FGD installation is highly recommended as one of the low cost clean technology option for Indian scenario.

Further, demand of power is increasing and domestic coal is in short supply and option available for coastal thermal power plants is either natural gas or imported coal.

6.3 LIMITATIONS OF THE STUDY

There are two noteworthy limitations of this study: generalizability and longitudinal effects. The generalizability of these research findings is limited because the LCA & LCC approaches are limited to two numbers of thermal power plants due to the unavailability of primary data. Second, time and budget limitations made it impractical to assess as collecting such data from foreign countries was beyond the scope of the current study. Future studies might consider narrative-based experiential learning interventions which are followed up with longitudinal check-ups for years or longer to explore if and how long-term after-effects actually occur. In view of the above constraints, the study focuses on LCA of imported coal and natural gas based thermal power plants to narrow down the objective of the research work. The study has following limitations:

- Life cycle analysis was carried out from ‘cradle to gate’ and not from ‘cradle to grave’ due to non-availability of data.
- Transport emissions have not been included in upstream processes for both cases i.e., imported coal and natural gas TPPs due to non-availability of data.
- Resource analysis has not been carried out due to non-availability of indigenous data related to mining and extraction of natural gas.
- In economic analysis, unit damage cost has been taken from other studies conducted in other countries, which might not give a true picture for Indian scenario and could have variable uncertainties.

6.4 FUTURE SCOPE

One can further study environmental and economic impacts in more detail where it could be investigated by collecting indigenous data for alternative technologies such as IGCC, SC and CCS in thermal power plants. Further, study could be analyzed from ‘cradle to grave’ including resource analysis with indigenous data, which can help decision makers for future policy planning for power sector taking into consideration climate change and human health. For economic analysis, social and environmental components could be explored in more detail by including willingness to pay and emission modelling for realistic assessment of exposure on local population.

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APPENDIX A
SAMPLE - DATA SPREAD SHEET

Table A.1: Input sheet for flue gas desulphurization system

S. No.	**Input**	***Source***	***Quantity (Units)***
1	Electricity consumption by flue gas ID fans		
2	Electricity consumption by Inlet damper		
3	Electricity consumption by pitch control booster fan		
4	Electricity consumption by Oxidation air blower		
5	Electricity consumption by Agitators		
6	Electricity consumption by mist eliminator (pump)		
7	Electricity consumption by recirculation pumps		
8	Electricity consumption by emergency bleed transfer pump		
9	Electricity consumption by quencher		
10	Electricity used for ventilation and air conditioning system		
11	Electricity consumed by wastewater pump		
12	Electricity used to pump wastewater (floor wash and flushing, cooling etc.) to treatment plant		
13	Electricity consumption by Outlet damper		
14	Electricity consumption by agitator in emergency slurry tank		
15	Electricity consumption by ambient air purge fan		
16	Limestone slurry consumption		

17	Volume of water consumed by absorber		
18	Inlet gas volume		
19	Outlet gas volume		
20	Volume of wastewater released from the unit		
21	Amount of gypsum bleed produced		
22	Lubricant used for ambient air purge fan		
23	Lubricant used for Inlet damper		
24	Lubricant used for outlet damper		
25	Lubricant used for pitch control booster fan		
26	Lubricant used for oxidation air blower		
27	Lubricant used for Mist eliminator (pump)		
28	Lubricant used for agitator		
29	Lubricant used for agitator in emergency slurry tank		
30	Lubricant used for recirculation pumps		

APPENDIX B

INPUT DATA

Table B.1: Input data for coal thermal power plant with FGD system

Products	**Quantity**	**Units**
Hard coal, burned in power plant with FGD	1	kWh
Materials/fuels		
Hard coal supply mix	0.402030	kg
Heavy fuel oil, at regional storage	1.0	ml
Water, completely softened, at plant	0.67	% MCR
SOx retained, in hard coal flue gas desulphurization	98	%
Water, deionized, at plant	0.067085	kg
Emissions to air		
Heat, waste	5.14066	MJ
Antimony	7.86E-10	kg
Arsenic	3.03E-09	kg
Barium	5.22E-08	kg
Benzene	2.18E-06	kg
Benzo(a)pyrene	2.01E-12	kg
Boron	2.13E-06	kg
Bromine	8.53E-07	kg
Butane	1.91E-07	kg
Cadmium	9.11E-10	kg
Carbon dioxide, fossil	0.96010	kg
Carbon monoxide, fossil	8.05E-05	kg
Chromium	2.12E-09	kg
Chromium VI	2.63E-10	kg
Cobalt	1.84E-09	kg
Copper	9.08E-09	kg

Dinitrogen monoxide	3.92E-05	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	7.04E-14	kg
Ethane	4.12E-07	kg
Formaldehyde	5.83E-07	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2.2E-06	kg
Hydrocarbons, aliphatic, unsaturated	2.17E-06	kg
Hydrogen chloride	3.62E-05	kg
Hydrogen fluoride	2.76E-05	kg
Iodine	1.6E-07	kg
Lead	6.28E-08	kg
Lead-210	7.56E-06	kBq
Manganese	2.6E-08	kg
Mercury	1.49E-08	kg
Methane, fossil	1.01E-05	kg
Molybdenum	1.6E-09	kg
Nickel	1.73E-08	kg
Nitrogen oxides	0.000617	kg
PAH, polycyclic aromatic hydrocarbons	1.01E-08	kg
Particulates, < 2.5 um	2.74E-05	kg
Particulates, > 10 um	5.19E-05	kg
Particulates, > 2.5 um, and < 10um	3.22E-06	kg
Pentane	1.48E-06	kg
Polonium-210	1.38E-05	kBq
Potassium-40	1.62E-05	kBq
Propane	3.52E-07	kg
Propene	1.61E-07	kg
Radium-226	1.95E-06	kBq
Radium-228	1.96E-06	kBq

Radon-220	0.002847	kBq
Radon-222	0.00505	kBq
Selenium	4.45E-08	kg
Strontium	7.8E-09	kg
Sulfur dioxide	0.000465	kg
Thorium-228	1.06E-06	kBq
Thorium-232	1.66E-06	kBq
Toluene	1.1E-06	kg
Uranium-238	1.63E-06	kBq
Vanadium	5.23E-09	kg
Xylene	9.28E-06	kg
Zinc	4.57E-08	kg
Emissions to water		
Heat, waste	1.3581	MJ
Waste to treatment		
Disposal, hard coal ash, 0% water, to residual material landfill	0.005503	kg
Disposal, residue from cooling tower, 30% water, to sanitary landfill	5.03E-05	kg

Table B.2: Input data for coal thermal power plant without FGD system

Products	**Quantity**	**Units**
Hard coal, burned in power plant without FGD, for combustion process	1	kWh
Materials/fuels		
Hard coal supply mix	0.498603	kg
Heavy fuel oil, at regional storage	0.00016	kg
Water, completely softened, at plant	0.281879	kg

Water, deionised, at plant	0.067085	kg
Emissions to air		
Heat, waste	5.70402	MJ
Antimony	1.99E-08	kg
Arsenic	1.22E-07	kg
Barium	1.23E-06	kg
Benzene	2.18E-06	kg
Benzo(a)pyrene	2.01E-12	kg
Boron	7.04E-06	kg
Bromine	5.74E-06	kg
Butane	1.91E-07	kg
Cadmium	1.17E-08	kg
Carbon dioxide, fossil	0.9601	kg
Carbon monoxide, fossil	8.05E-05	kg
Chromium	1.15E-07	kg
Chromium VI	1.42E-08	kg
Cobalt	4.72E-09	kg
Copper	1.54E-07	kg
Dinitrogen monoxide	5.03E-06	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	7.04E-14	kg
Ethane	4.12E-07	kg
Formaldehyde	5.83E-07	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2.2E-06	kg
Hydrocarbons, aliphatic, unsaturated	2.17E-06	kg
Hydrogen chloride	0.000307	kg
Hydrogen fluoride	2.75E-05	kg
Iodine	2.94E-06	kg
Lead	6.36E-07	kg

Lead-210	0.001217	kBq
Manganese	6.07E-07	kg
Mercury	3.22E-08	kg
Methane, fossil	1.01E-05	kg
Molybdenum	2.16E-08	kg
Nickel	3.35E-07	kg
Nitrogen oxides	0.004104	kg
PAH, polycyclic aromatic hydrocarbons	1.01E-08	kg
Particulates, < 2.5 um	0.000426	kg
Particulates, > 10 um	0.000107	kg
Particulates, > 2.5 um, and < 10um	5E-05	kg
Pentane	1.48E-06	kg
Polonium-210	0.002233	kBq
Potassium-40	0.000301	kBq
Propane	3.52E-07	kg
Propene	1.61E-07	kg
Radium-226	0.000316	kBq
Radium-228	9.34E-05	kBq
Radon-220	0.006539	kBq
Radon-222	0.003682	kBq
Selenium	9.95E-08	kg
Strontium	1.12E-06	kg
Sulfur dioxide	0.007477	kg
Thorium-228	5.03E-05	kBq
Thorium-232	7.91E-05	kBq
Toluene	1.1E-06	kg
Uranium-238	0.000263	kBq
Vanadium	2.81E-07	kg

Xylene	9.28E-06	kg
Zinc	7.75E-07	kg
Emissions to water		
Heat, waste	1.4587	MJ
Waste to treatment		
Disposal, hard coal ash, 0% water, to residual material landfill	0.005503	kg
Disposal, residue from cooling tower, 30% water, to sanitary landfill	5.03E-05	kg
Hard coal, burned in power plant without FGD, for combustion process	1	kWh

Table B.3: Input data for NGCC thermal power plant

Products		
electricity from Natural gas, burned in power plant	1	kWh
Materials/fuels		
Natural gas, at long-distance pipeline	0.249	m3
Water, decarbonised, at plant	0.75	kg
Electricity/heat		
Electricity, industrial gas, at power plant	3.00%	%
Emissions to air		
Heat, waste	0.79	MJ
Nitrogen oxides	1.04E-04	kg
Carbon monoxide, fossil	3.10E-05	kg
Carbon dioxide, fossil	4.26E-01	kg
Sulfur dioxide	1.30E-05	kg
Particulates, < 2.5 um	6.20E-05	kg
Dinitrogen monoxide	1.00E-06	kg

Mercury	3.00E-11	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	2.90E-17	kg
Methane, fossil	4.40E-05	kg
Acetaldehyde	8.00E-10	kg
Benzo(a)pyrene	5.29E-13	kg
Benzene	9.26E-10	kg
Butane	9.26E-07	kg
Acetic acid	1.21E-07	kg
Formaldehyde	1.10E-05	kg
PAH, polycyclic aromatic hydrocarbons	8.00E-09	kg
Pentane	1.15E-06	kg
Propane	7.05E-07	kg
Propionic acid	1.60E-08	kg
Toluene	1.50E-09	kg
Acenaphthene	7.93E-13	kg
Ethane	1.37E-06	kg
Hexane	7.93E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.30E-05	kg
Waste to treatment		
Disposal, residue from cooling tower, 30% water, to sanitary landfill	1.00E-05	kg

APPENDIX C

RESULTS - ENVIRONMENTAL IMPACTS

Table C1: Contribution of significant pollutants causing various environmental impacts from 1 kWh electricity generation from imported coal thermal power plant (cradle to gate)

Impact category	Contribution from different substances	Units	Amount	Total	Percentage
CML 2001 Method – midpoint impacts					
Acidification	Nitrogen oxides	kg SO_2 eq.	2.23E-03	1.47E-02	15.20
	Sulfur dioxide	kg SO_2 eq.	1.21E-02		82.49
	Remaining substances (ammonia, hydrogen chloride etc.)	kg SO_2 eq.	3.39E-04		2.31
Eutrophication	Nitrogen oxides	kg PO_4 eq.	5.81E-04	1.18E-03	49.45
	Phosphates	kg PO_4 eq.	5.75E-04		48.94
	Remaining substances (ammonia, ammonium ion, COD etc.)	kg PO_4 eq.	1.90E-05		1.62
Global Warming	Carbon dioxide	kg CO_2 eq.	1.01E+00	1.12E+00	90.00
	Methane	kg CO_2 eq.	1.08E-01		9.60
	Remaining substances (CO, N2O etc.)	kg CO_2 eq.	4.49E-03		0.40
Fresh water aquatic toxicity	Beryllium	kg I,4-DB eq.	3.00E-02	1.31E-01	22.92
	Nickel ion	kg I,4-DB eq.	5.39E-02		41.18
	Remaining substances (vanadium ion, cobalt etc.)	kg I,4-DB eq.	4.70E-02		35.91
Human toxicity	Arsenic	kg I,4-DB eq.	4.56E-02	1.40E-01	32.66
	Chromium VI	kg I,4-DB eq.	5.23E-02		37.46
	Remaining substances (nickel, PAH, benzene etc.)	kg I,4-DB eq.	4.17E-02		29.87
Marine aquatic	Beryllium	kg I,4-DB eq.	1.09E-01	4.79E-01	22.76

Impact category	Contribution from different substances	Units	Amount	Total	Percentage
toxicity	Nickel ion	kg I,4-DB eq.	1.84E-01		38.41
	Remaining substances (vanadium ion, cobalt etc.)	kg I,4-DB eq.	1.86E-01		38.83
Eco-indicator-99(H) – endpoint impacts					
Acidification/Eutrophication	Nitrogen oxides	PDF × m^2 × yr	2.55E-02	3.60E-02	70.77
	Sulfur dioxide	PDF × m^2 × yr	1.05E-02		29.14
	Remaining substances (ammonia, sulfate etc.)	PDF × m^2 × yr	3.32E-05		0.09
Carcinogens	Arsenic ion	DALY	1.05E-07	1.29E-07	81.40
	Cadmium ion	DALY	1.08E-08		8.37
	Remaning substances (particulate matter, chromium VI etc.)	DALY	1.32E-08		10.23
Climate change	Carbon dioxide	DALY	2.53E-07	2.94E-07	86.06
	Methane	DALY	4.05E-08		13.78
	Remaining substances (N2O, CO etc.)	DALY	4.64E-10		0.16
Ecotoxicity	Nickel	PAF × m^2 × yr	2.56E-02	7.35E-02	34.83
	Nickel ion	PAF × m^2 × yr	2.39E-02		32.52
	Remaining substances (lead, chromium ion, zinc etc.)	PAF × m^2 × yr	2.40E-02		32.65
Resp. inorganics	PM <2.5	DALY	5.81E-07	1.57E-06	37.03
	Sulfur dioxide	DALY	5.52E-07		35.18
	Remaining substances (PM10, NOx etc.)	DALY	4.36E-07		27.79
Resp. organics	Methane	DALY	1.18E-10	1.62E-10	72.84
	Xylene	DALY	1.19E-11		7.35
	Remaining substances (NMVOC, aliphatic unsaturated	DALY	3.21E-11		19.81

Impact category	Contribution from different substances	Units	Amount	Total	Percentage
	hydrocarbons, toluene etc.)				

Table C2: Contribution of significant pollutants causing various environmental impacts from 1 kWh electricity generation in CCNG thermal power plant (cradle to gate)

Impact category	Contribution from different substances	Units	Amount	Total	Percentage
CML 2001 Method – midpoint impacts					
Acidification	Nitrogen oxides	kg SO_2 eq.	1.78E-04	5.27E-04	33.79
	Sulfur dioxide	kg SO_2 eq.	3.32E-04		63.02
	Remaining substances	kg SO_2 eq.	1.68E-05		3.19
Eutrophication	Nitrogen oxides	kg PO_4 eq.	4.63E-05	6.88E-05	67.26
	Phosphates	kg PO_4 eq.	2.11E-05		30.65
	Remaining substances	kg PO_4 eq.	1.44E-06		2.09
Global Warming	Carbon dioxide	kg CO_2 eq.	5.31E-01	5.77E-01	92.40
	Methane	kg CO_2 eq.	4.24E-02		7.04
	Remaining substances	kg CO_2 eq.	3.22E-03		0.56
Fresh water aquatic toxicity	Beryllium	kg I,4-DB eq.	9.14E-04	4.25E-03	21.49
	Nickel ion	kg I,4-DB eq.	1.99E-03		46.78
	other substances	kg I,4-DB eq.	1.35E-03		31.73
Human toxicity	PAH	kg I,4-DB eq.	4.56E-02	5.67E-02	80.37
	Benzene	kg I,4-DB eq.	1.02E-02		17.98

Impact category	Contribution from different substances	Units	Amount	Total	Percentage
	Remaining substances	kg I,4-DB eq.	9.37E-04		1.65
Marine aquatic toxicity	Beryllium	kg I,4-DB eq.	3.31E-03	1.51E-02	21.88
	Nickel ion	kg I,4-DB eq.	6.80E-03		44.94
	other substances	kg I,4-DB eq.	5.02E-03		33.18
Eco-Indicator 99(H) Method – endpoint impacts					
Acidification/Eutrophication	Nitrogen oxides	PDF × m^2 × yr	2.04E-03	2.27E-03	89.76
	Sulfur dioxide	PDF × m^2 × yr	2.28E-04		10.03
	Remaining substances	PDF × m^2 × yr	4.81E-06		0.21
Carcinogens	Arsenic ion	DALY	1.92E-09	3.37E-09	56.94
	Particulate < 2.5µm	DALY	7.56E-10		22.42
	Remaining substances	DALY	6.96E-10		20.64
Climate change	Carbon dioxide	DALY	1.11E-07	1.19E-07	92.89
	Methane	DALY	7.72E-09		6.46
	Remaining substances	DALY	7.76E-10		0.65
Ecotoxicity	Nickel	PAF × m^2 × yr	1.71E-04	1.54E-03	11.10
	Nickel ion	PAF × m^2 × yr	8.84E-04		57.40
	Remaining substances	PAF × m^2 × yr	4.85E-04		31.49
Resp. inorganics	Nitrogen oxides	DALY	3.16E-08		30.68

Impact category	**Contribution from different substances**	**Units**	**Amount**	**Total**	**Percentage**
	Particulate < 2.5 µm	DALY	5.41E-08	1.03E-07	52.52
	Remaining substances	DALY	1.73E-08		16.80
Resp. organics	NMVOC	DALY	3.07E-10	3.98E-10	77.17
	Methane	DALY	2.25E-11		5.66
	Remaining substances	DALY	6.83E-11		17.17

KULDEEP KUMAR AGRAWAL

Academic Credentials: B.E. (Mechanical Engg), PG diploma in Thermal Power Plant and MBA Operations.

Professional Synopsis: An astute Engineer with over 9.0 years of experience in thermal power plants and energy sector.

Research Publications

International Journals

Agrawal, K. K., Jain, S., & Jain, A. K. (2012). Assessment of environmental impacts of natural gas combined cycle thermal power plant using life cycle approach. The International Journal of Life Cycle Assessment (Communicated on 19-10-2012).

Agrawal, K. K., Jain, S., Jain, A. K., & Roy, H. (2012). Assessment of greenhouse gas emissions from imported coal and natural gas combined cycle thermal power plants using life cycle approach in India. Energy Conversion and Management (Communicated on 22-09-2012).

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National Journals

Agrawal, K. K., Jain, S., Jain, A. K., & Roy, H. (2012). Externalities in Power Industries: An Impact Assessment of Hidden Costs of Power Generation through Imported Coal and Natural Gas Based Thermal Power Plants in India. Tenth AIMS International Conference on Management. Bangalore: Indian Institute of Management Bangalore (Accepted).

International Conferences

Agrawal, K. K., Jain, S., & Jain, A. K. (2012). Application of life cycle assessment in identifying and reducing environmental impacts of thermal power plants in India. Changing Dynamics in the Global Village. Noida: Symbiosis Centre For Management Studies (Accepted).

Agrawal, K. K., Jain, S., Jain, A. K., & Roy, H. (2012). Life Cycle Environmental And Economic Impacts Assessment of Thermal Power Plants. Tenth AIMS International Conference on Management. Bangalore: IIM Bangalore (Accepted).