Study Report on

Estimation of External Cost of Thermal Power Generation

For

Public Utilities Commission of Sri Lanka

Final Draft Report

SLEMA

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EXECUTIVE SUMMERY

- Electricity generation, particularly through the fossil fuels fired thermal power plants, gives rise to a range of issues associated with emissions of byproducts in different forms. These emissions could lead to adverse impacts on local community, society at large and ecological system, both in the short run as well as in the long run. It is important to assess and quantify such externalities accurately to evaluate the true 'economic cost' of power generation.

- In the present methodology, a five step process is followed to identify and quantify the impacts of thermal power generation, as:
    1. Identification of different technologies used in thermal power plants in Sri Lanka.
    2. Identification of byproducts/pollutants emitted by these technologies/power plants.
    3. Quantification of pollution by each type of power plant.
    4. Establishment of the relationship between pollutants and possible impacts.
    5. Monetary valuation of the impacts using both primary and secondary data.

- The externalities of thermal power plants could be attributed to both their local impacts and global impacts. Emission of pollutants to surrounding environment resulting in quality degradation of the local environment and costs to the local economy is the local impact whereas the emission of Green House Gases (GHGs) and the consequential contribution to climate change, which is felt by the entire world is the global impact.

- Among all externalities caused by thermal power plants, adverse health effects are of special importance. The extent of the health effects depends on the magnitude and duration of the exposure to specific pollutants, and the nature of the exposed population.

- To identify the health impacts of thermal power generation, a desk review on studies done to assess mortality and morbidity on selected end points associated with targeted pollutants generated from coal and other fossil fuel-based power plants was carried out.

- Burning of coal leads to the emission of hazardous gases with many underlying health impacts. In coal combustion, there is formation of carbon dioxide (CO_2) and carbon monoxide (CO), sulphur dioxide (SO_2) and sulphur trioxide (SO_3), and nitrogen dioxide (NO_2) and nitric oxide (NO) and particulate matter (PM). These have been correlated with many health problems directly and indirectly.

- Particulates generated from coal power plants cause air pollution. A clear relationship between air pollution and developmental disorders, pregnancy outcomes, infant mortality and other genetic anomalies at both personalized and population levels have been shown.

- The formation of the poisonous SO_2 gas, a major pollutant in air, may accelerate the rate of diseases and decrease life expectancy in the vicinity of power plants. When SO_2 combines with water, it forms sulphuric acid, which is the main component of acid rain: a cause of deforestation.

- High levels of NO_2 in the air causes a reduction in the pulmonary function in humans, asthma attacks and genetic mutations. PM level, individually and in combination with NO_2

in air, leads to the development of serious diseases, including lung cancer, cardiovascular diseases, and reproductive disorders. The ozone gas formed as a result of NO_2 reaction with the volatile organic compounds in the air causes ozone-related asthma exacerbations in infants.

- Morbidity and mortality endpoints linked to key air pollutants are given in the table below.

Outcome	Disease	Pollutant
Mortality	Respiratory diseases Cardiovascular disease COPD (Chronic-obstructive pulmonary disease) Cerebrovascular events Ischemic heart disease Lung cancer	Particulate matter (PM_{10}, $PM_{2.5}$) Nitrogen oxides (NO_x) Sulphur oxides (SO_x) Carbon monoxide (CO) Ozone (O_3, formed from SO_x and VOC)
Hospital Admissions	Respiratory diseases (acute and chronic) COPD Cardiovascular disease Cerebrovascular events Chronic bronchitis Asthma Lower respiratory symptoms	Particulate matter (TPS, PM_{10}, $PM_{2.5}$) NO_x SO_x CO O_3 (formed from SO_x and VOC)
Restricted Activity Days		PM

- Particularly, in coal combustion-based power generation, the emission of COx, NOx, SOx, PM and some heavy metal pollutants are known to induce a wide range of health problems. COx is a major contributor to global warming and some diseases including COPD and lung cancers. Uncontrolled emission of SO_2 within SOx, causes a wide range of diseases including destabilization of the heartbeat, skin cancer, asthma, and cough, headache, throat, and nose irritations. NOx, another major pollutant from energy production coal power plant, is causing hypoxic respiratory failure mainly related to persistent pulmonary hypertension of newborn (PPHN).

- Collectively, COx, SOx and NOx have not only direct health impacts, but indirect impacts damaging the global food web due to acid rains. PM, along with COx, SOx and NOx are damaging both the environment and human health on a large scale. Heavy metal traces produced in coal combustion plants are also causing serious diseases, such as skin and lung cancer, cardiovascular diseases, abdominal pain, gene mutation, leukemia and comas resulting in death.

- Various measures taken to meet emission standards introduced to mitigate adverse impacts of thermal power generation are referred to as pollution control. Pollution control techniques include changes in processes or raw materials, modification of equipment and installation of devices at the end process equipment to treat the effluents. Comparison of best available technologies (BATs) or best available retrofit technologies (BARTs) would allow to establish the potential for further improvements in the environmental performance of power plants to satisfy regulatory requirements.

- Use of BATs/BARTs demands best operational performance of power plants as a prerequisite. Operational failures are not acceptable and should be corrected as a mandatory requirement. Hence, changing the emission control technology to cover up the deficiencies in operations are not be considered as a BAT/BART option.

- Typical BAT/BART with their control efficiencies for selected pollutants are given in the table below.

Pollutant	Control Processes/Technologies	Efficiency
SO_2	Wet Flue Gas Desulfurization (FGD)	90% – 98%
	Dry Flue Gas Desulfurization (FGD)	75% - 85%
	Dry sorbent injection (DSI)	70% - 75%
NO_X	Selective Catalytic Reduction (SCR)	70% - 90%
	Selective Non-Catalytic Reduction (SNCR)	30% - 50%
	Low-NOX burners	65% - 75%
Mercury (Hg)	Activated carbon injection (ACI)	80% – 90%
Acid gas	DSI	90% – 98%
	Wet FGD	90% – 98%
	Dry FGD	75% - 85%
PM / Metallic Toxics	Electrostatic Precipitation (ESP)	90% – 99.9%
	Fabric Filter (Baghouse)	99% – 99.9%

- Control of fugitive emissions from fuel transport, storage, and handling is very site specific and situational dependent, thus usually needs combination of specific control mechanisms and technologies. In particular, the dust emissions from coal yards and ash storage facilities in coal power plants could be controlled by the use of wind fences, water misters and/or chemical dust suppressants.
- The below table presents an estimate on incremental cost of energy due to incorporation of BAT for air emission control of a coal power plant.

Pollutant	Control Technology	Total Generation (t/yr)	Amount Captured (t/yr)	Abatement Cost (US$/t)	Incremental Cost of Electricity (Rs./kWh)
SO_2	Wet FGD	16,819	15,978	639.83	0.851
NO_X	SCR	6,240	5,616	736.64	0.344
Hg	ACI	0.168	0.151	2,338,597.16	0.029
PM	Baghouse	116,052	114,892	43.48	0.416
Fugitive Emissions	Wind fencing + Water misting	54.45	51.18	21,745.50	0.093
Total Incremental Cost of Electricity					**1.733**

- To exemplify the estimation of externality cost of a power plant, four thermal power plants in Sri Lanka are selected as case studies, based on the generation technology and the type of fuel used. The selected thermal power plants are:
    1. Lak Vijaya Power Plant (LVPP) in Norochcholai
    2. Yagadhanavi Power Plant in Kerawalapitiya,
    3. Kelanitissa Power Station in Peliyagoda,
    4. Sapugaskanda Power Plant in Sapugaskanda.

- Estimated externality cost of LVPP due to emission of GHGs is during 2011-2017 is presented below;

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(US Cts /kWh)	(Rs./kWh)
2011	34,057,735	3,780,408,680	1,038.10	3.28	3.64
2012	56,124,814	7,183,976,105	1,403.70	4.00	5.12
2013	63,921,576	8,245,883,349	1,469.40	4.35	5.61
2014	135,705,025	17,641,653,311	3,524.10	3.85	5.01
2015	195,071,390	26,529,709,049	4,457.80	4.38	5.95
2016	224,152,974	32,726,334,162	5,066.90	4.42	6.46
2017	244,115,969	36,617,395,248	5,120.60	4.77	7.15

- Local externality cost of LVPP was estimated using two approaches. A household survey was conducted in the locality LVPP to identify the impact and damage cost on agriculture, health, and fishery. For other externalities not captured by the household survey, such as stack emissions, fugitive emissions, pollution control measures, benefit transfer approach and market price approaches weres used to estimate the externality cost. Below table summarizes the total externality cost, which is presented as a range between the lower bound estimate and the upper bound estimate.

Item	Total Damage Cost (Rs. per year) (Lower Bound)	Total Damage Cost (Rs. per year) (Upper Bound)
Damage cost estimated based on household surveys and key informant interviews conducted among nearby communities focusing on agricultural, health household mitigation measures and fishery impacts	1,609,341,303	2,603,091,303
Costs of air pollutants estimated using benefit transfer approach	13,906,995,550	
Costs of water used and costs of other mitigation measures incurred at the plant	258,252,638	
Total	15,774,589,491	16,768,339,491

- Below table provides externality costs in relation to power generated by LVPP.

Parameter	Lower Bound Estimate	Upper Bound Estimate
External Costs calculated using Approach 1 and 2		
External cost in Rs.	**15,774,589,491**	16,768,339,491
External cost in US$	90,140,511	95,819,083
External cost in US$ per kWh (considering the annual generation of 5120.60 GWhrs)	0.01760	0.01871
External cost in US$ cents per kWh	**1.7603**	**1.8712**
External cost in Rs. per kWh	**3.080**	**3.275**
External costs due to emission of GHGs[1]		
External cost in US$ cents per kWh	**4.77**	**4.77**
External cost in Rs. per kWh	**7.15**	**7.15**

Final total External cost per kWhr		
Total external cost of LVPP in US$ cents per kWh	**6.53**	**6.641**
Total external cost of LVPP in Rs per kWh	**10.231**	**10.425**

[1]Estimated for the year 2017

- Estimated externality cost of Yugadhanavi Power Plant due to emission of GHGs during 2011-2017 is presented below.

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	22,995,884	2,552,543,064	1,186.0	2.10	2.33
2012	31,418,344	4,021,547,976	1,465.0	2.37	3.03
2013	9,203,927	1,187,306,541	460.2	2.25	2.91
2014	14,251,316	1,852,671,041	657.6	2.49	3.24
2015	15,484,767	2,105,928,418	671.4	2.70	3.68
2016	22,488,909	3,283,380,720	891.8	3.01	4.40
2017	29,539,716	4,430,957,389	1,193.6	3.02	4.53

- Estimated externality cost of Kelanitissa Power Station due to emission of GHGs during 2011-2017 is presented below.

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	11,431,576	1,267,607,639	320.3	3.87	4.30
2012	8,301,946	1,061,137,514	218.2	4.21	5.38
2013	647,487	81,850,795	17.6	4.07	5.25
2014	8,835,544	1,146,957,156	241.9	4.20	5.46
2015	963,840	129,317,074	25.1	4.45	6.05
2016	12,243,017	1,785,616,313	308.5	4.75	6.94
2017	16,529,109	2,477,314,284	401	5.03	7.55

- Estimated externality cost of Sapugaskanda Power Station due to emission of GHGs during 2011-2017 is presented below.

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	18,752,470	2,081,524,199	910.9	2.23	2.47
2012	19,631,315	2,512,808,270	925.8	2.34	3.00
2013	12,513,570	1,614,250,516	572.9	2.46	3.17
2014	14,825,681	1,927,338,514	656.3	2.59	3.37
2015	6,944,824	944,495,976	294.4	2.76	3.76
2016	19,286,386	2,815,059,908	784.8	2.94	4.29
2017	17,609,896	2,640,988,255	692.7	3.10	4.65

- It is important to highlight as a concluding remark that the estimation of impacts of externalities in financial terms needs accurate data and information relevant to a specific power plant and its locality. Lack of such data and the level of accuracy affect the precision of the final results. However, the methodology proposed in this study is recommended as a sound approach for the analysis and estimation of the impact of externalities in thermal power plants and collection of required data should be part of the regulatory and operational conditions of the approvals of power plants

In conclusion, when the cost per kWh is compared it is evident that the highest externality cost is resulted from the LVPP which is Rs 10.23 (when the lower bound value is considered).

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1 INTRODUCTION

1.1 Project Description

Since April 2009, Public Utilities Commission of Sri Lanka (PUCSL) has been regulating the electricity industry in Sri Lanka. As part of this regulation process, PUCSL has to review and approve the Long Term Generation Expansion Plan (LTGEP) prepared by the Ceylon Electricity Board (CEB), which follows economic least cost principles in identifying the optimal generation capacity mix to meet the electricity demand of the country forecast over a period of twenty years. To review and accept the proposed generation plan prepared bi-annually by the CEB, PUCSL needs to make judgements on the accuracy and validity of the data and assumptions used in the plan. One such parameter under review by the PUCSL is the externality cost of existing and proposed thermal power generation in Sri Lanka, as the economic cost essentially include monetary as well as non-monetary costs incurred by the country. These externalities are not appraised in the present process of LTGEP.

With the objective of estimating the social and environmental damage cost associated with fossil fuel based thermal power generation, PUCSL commissioned this study in October 2018. It is expected that the estimated externality values would be used for selecting the optimal technologies for power generation in Sri Lanka in the process of LTGEP.

Sri Lanka Energy Managers Association (SLEMA), the pioneering energy management institution dedicated for promotion and knowledge sharing on energy management and efficiency improvement in Sri Lanka, was selected to conduct the study. SLEMA fielded a multidisciplinary team of experts to cover different aspects of the study and this report presents the compilation of finding of the study.

1.2 Background

1.2.1 Evolution of the Sri Lankan Power Sector

Primarily to supply a limited customer base in and around Colombo area, Electricity Board of Ceylon was established in 1935. In 1937, the Department of Government Electrical Undertakings was established, assigning the responsibility to expand the electricity supply over the entire country. In 1950, Laxapana Power Station was commissioned as the first centralised power station in the country, followed by several more power generation projects, mainly using the large hydro resource abundantly available in the country.

In 1969, Ceylon Electricity Board (CEB) was established as a full-fledged linearly integrated electrical utility to serve an island wide customer network. CEB was assigned with the responsibility of planning and developing the necessary generation, transmission, and distribution systems to cater the expanding national electricity demand. Accordingly, CEB has carried out regular generation capacity additions: initially large scale hydro power plants and more recently, thermal power plants and small scale renewable based power generating facilities.

1.2.2 Present Status and Future Outlook

Currently, the national electricity demand is met by nine thermal power stations, fifteen large hydroelectric power stations, close to two hundred mini hydro power plants, fifteen wind farms and more than twenty solar and biomass power plants. Majority of the hydroelectric and thermal/fossil fuel–based power stations in the country are owned and operated by the CEB.

National electricity generation capacity improvement and energy generation is shown in Figure 1.1.

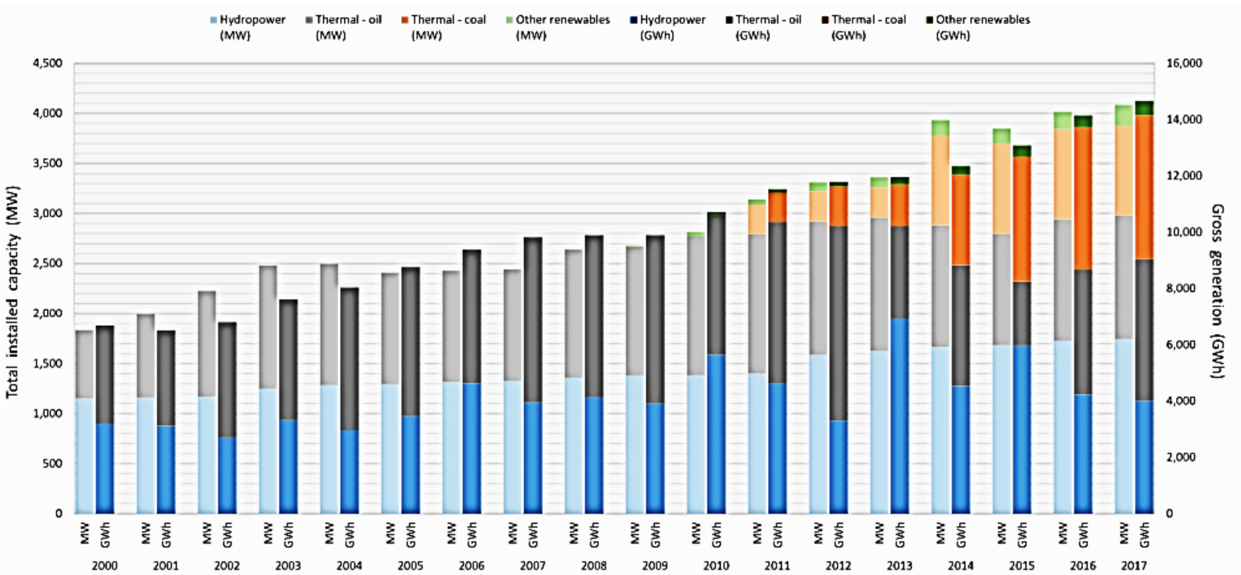

Figure 1.1: National Electricity Grid Capacity Development

Renewable and non-renewable based power plants have different environmental impacts at different stages of the power plant lifecycle. Environmental impacts of renewable energy power plants are prominent during the construction stage whereas in thermal power plants, the environmental impacts are mostly felt during the operational stages. Usually, environmental impacts during operation of thermal power plants within their lifetime outweighs the life-cycle environmental impacts of renewable energy plants, highlighting the importance of life-cycle assessments for comparison.

Considering the lower construction cost, smaller physical footprint, possibility to store the fuel and use as and when required; fossil fuel based thermal power plants such as coal, liquid petroleum and natural gas power plants have been opted for over renewable energy power plants. On the other hand, renewable power generation options such as run-of-the-river hydro, solar PV and wind turbines have the limitation of intermittent availability due to the diurnal and seasonal variation and the fluctuation of the resource, causing technical challenges in maintaining power system stability and reliability.

1.3 Externalities - Theory and Policy Implications

Electricity generation, particularly through the fossil fuels fired thermal power plants, gives rise to a range of issues associated with emissions of byproducts in different forms, depending on the type of fuel and technology employed. These emissions could lead to adverse impacts on local community, society at large and ecological system, both in the short run as well as in the long run. It is important to assess and quantify such externalities accurately to evaluate the true ‘economic cost’ of power generation.

Economic externalities represent the impacts of production and consumption onto entities other than those producing and consuming, which are not reflected in prices. While externalities can be either positive or negative, this study intends to quantify negative environmental and societal externalities. The classic example is that of the private owner of a coal power plant paying for coal, labour and other inputs and charging for the energy sold, but not bearing a cost for the damages to health and nature caused by, for example, the air pollution the power plant causes. These costs are borne by the society (as a whole), so that the outcomes for individual entities and the society differ.

In a perfect market, which maximises social welfare, private costs would be equal to societal costs, with no externalities to the price mechanism and all the costs and benefits to society of economic activity reflected in the price. Without policy interventions, this is rarely the case, with the most common scenario being the lower prices and higher consumption than is desirable for society as a whole (Figure 1.2). It is necessary therefore to 'internalise' the externalities, through policy interventions such as taxes, regulations, subsidies, and other measures. These modify the prices and incentives for private production and consumption decisions so that they account for the full impact on social welfare.

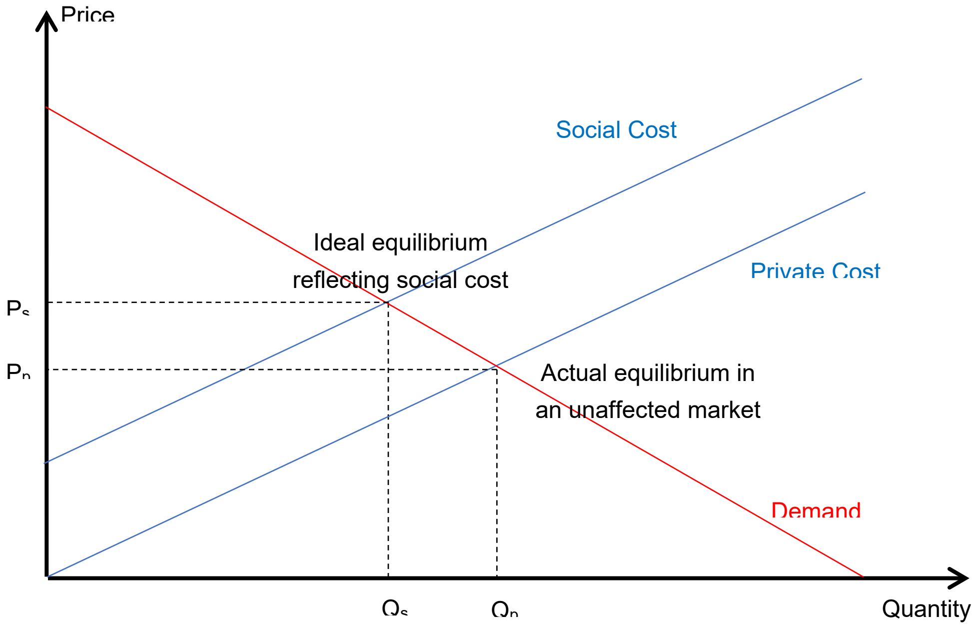

Figure 1.2: Difference in Private and Societal Costs

2 STUDY APPROACH

2.1 Externalities of Different Power Generation Technologies

The methodology proposed in the present study includes a five step process to identify and quantify the impacts of different power generating technologies, as described below:

Step 1 – Identification of different technologies used or in contention for future use in thermal power plants in Sri Lanka. Power generation technologies are identified by the combination of (i) the fuel and (ii) the energy conversion technology used in the plant.

Step 2 – Identification of byproducts/pollutants emitted by thermal power plants. Various emission processes and the related byproducts/pollutants are identified, particularly covering the following:

- Combustion emissions, including criteria pollutants such as particulate matter (PM), sulphur oxides (SOx), nitrogen oxides (NOx), and heavy metals including mercury (Hg) compounds,
- Fugitive emissions from fuel transport, storage, and handling,
- Spillage and dispersion of materials during transport, storage, and handling,
- Discharge of hot water and effluents with special focus on nearshore marine life / ecosystem,
- Withdrawal / discharge from water bodies (including marine), and
- Handling and disposal of toxic materials / residues.

Step 3 – Quantification of pollution by different types of power plants
There are various types of gaseous, liquid and solid pollutants emitted during the life-cycle of a thermal power plant. The qualitative and quantitative characteristics of the emissions depend on many factors including the technology, fuel type, fuel quality, capacity, age of the power plant, operational procedures & level of maintenance, types of emission control technologies adopted, and operational conditions of the emission control technologies. Further, the impacts of these pollutants are primarily determined by their contribution to the ambient concentrations and depositions in air, water, soil, and other elements in the biosphere. The ambient concentrations and depositions of pollutants are determined by not only the emission from the sources but also the characteristics of dispersion through air, water, and soil, which in turn are affected by weather conditions and the climate.

The main stages and elements of physical quantification of the pollutants emitted and their concentrations in the ambient environment by a given power plant can be summarized as follows:

- Characterize qualitatively the emission processes and related pollutants.
- Quantify the emission of different pollutants emitted by the power plant.
- Model the dispersion of the pollutants

Step 4 – Establishment of the relationship between different pollutants and impacts
Major impacts due to the power plants could be identified from primary sources as well as secondary sources of information. A field survey among the surrounding communities of a selected power plant should carryout to assess the existing situation. In addition, stakeholder interviews should be conducted with pre-tested questionnaire to further identify and verify the significant impacts.

Step 5 – Monetary valuation of the impacts using both primary and secondary data.

2.2 Level of Impact

The externalities of thermal power plants could be attributed to both their local impacts and global impacts. Emission of pollutants to surrounding environment resulting in quality degradation of the local environment is the local impact whereas the emission of Green House Gases (GHGs) and the consequential contribution to climate change is the global impact.

Establishing the relationship between emission source/activity and local impacts is relatively straightforward (compared to localization of global impacts) and could be achieved by collection of information at local level. However, the local impact due to climate change is not only related to local emission source/activity, thus becomes a global phenomenon, and therefore more difficult to establish. Even in the case of local level, the impacts on the immediate surroundings and the other areas of the country would be distinctly different. In addition, presence of other emissions sources in the vicinity of the impact areas makes the establishment of source-impact relationship more complex. Furthermore, methodologies used in analysing these impacts are different and sources of information/data too are diverse. Therefore, the formulation of a sound methodology becomes central to any effort for not only in establishing the relationship between emission sources/activity and local impacts, but also in internalizing the externalities.

2.3 Case Studies

Four thermal power plants in Sri Lanka are selected as case studies, based on the generation technology and the type of fuel used, to estimate the cost of externalities of each technology type. The selected thermal power plants are:

1. Lak Vijaya Power Plant (LVPP) in Norochcholai
2. Yagadhanavi Power Plant in Kerawalapitiya,
3. Kelanitissa Power Station in Peliyagoda,
4. Sapugaskanda Power Plant in Sapugaskanda.

For LVPP, both the global and local externalities have been estimated as a comprehensive case study. Due to limitation of time and lack of data, the case studies for other three power plants have been limited to estimating their global externalities. However, the methodology developed is equally applicable across all the thermal power plants. It is important to note at this stage that the effective use of the proposed methodology needs accurate and sufficient data/information relevant to a specific power plant and its locality. Lack of such data/information and their level of accuracy affect the precision of the final results, thus in turn could limit the applicability of the methodology.

3 TYPES OF THERMAL POWER GENERATION

Thermal power plants are categorised based on the combination of (i) the energy conversion technology and (ii) the fuel used by the power plant. Table 3.1 lists the different energy conversion technologies and fuels typically used in thermal power plants.

Table 3.1: Types of Thermal Power Plants

Energy Conversion Technology	Fuel
• Steam Turbines • Combined Cycle Power Plants (CCY) • Open Cycle Gas Turbine (GT) • Diesel Engines	• Natural Gas (CNG/LNG) • Diesel • Naphtha • Heavy Fuel Oil (HFO) • Furnace Oil (FO) • Coal • Nuclear • Biomass

In combination of the different fuels and power generation technologies listed above, the following types of power plants are found or proposed in Sri Lanka:

- Steam turbine power plants using coal
- Combined cycle power plants using natural gas (planned)
- Combined cycle power plants using diesel
- Combined cycle power plants using HFO
- Open cycle gas turbine power plants using diesel
- Diesel engine power plants using diesel
- Diesel engine power plants using HFO

3.1 Different Types of Fuels used for Thermal Power Generation in Sri Lanka

3.1.1 Coal

Coal deposits are widely distributed around the world. Therefore, coal prices are generally stable in comparison with other fuels such as petroleum and natural gas. Also, for a unit energy contained in the fuel, price of coal is much lower compared with most other fuels. Thus, coal has been the preferred fuel source for thermal power generation in most countries.

Properties characterising coal as a fuel include moisture, ash, volatile matter, and fixed carbon content, caking tendencies, reactivity, ash fusion characteristics and particle size distribution. Based on the above characteristics, coal is categorised into four types.

- Lignite,
- Sub-bituminous coal,
- Bituminous coal, and
- Anthracite.

In Sri Lanka, bituminous coal is used as a fuel in coal power plants. Bituminous coal or black coal is a relatively soft coal containing a tar-like substance called bitumen. It is of higher quality than lignite coal but of poorer quality than anthracite. Formation of bituminous coal is usually the result of high pressure being exerted on lignite. Its coloration can be black or sometimes dark brown.

Bituminous coal contains 77-87 % carbon, whereas anthracite coal contains more than 87% carbon. However bituminous coal is more abundant than anthracite coal. Table 3.2 provides the specifications of bituminous coal imported from South Africa for the use of LVPP, as reported by CEB to the PUCSL.

Table 3.2: Specifications of Coal used in Sri Lankan Coal Power Plants

	GCV (kcal/kg)	Moisture %	Ash %	Sulphur %
Average	6,196	7.05	14	0.52
Minimum	5,909	5.23	16	0.77
Threshold	6,300	12%	11%	31%
% lower than threshold	86%	100%	0%	0%
% higher than threshold	14%	0%	100%	100%
2nd threshold	N/A	N/A	15%	N/A
% higher than 2nd threshold	N/A	N/A	17%	N/A

GCV = Gross Calorific Value; N/A – Not Applicable.

Source: Public Utilities Commission of Sri Lanka

3.1.2 Natural Gas

Natural gas is a fossil fuel that has been created by organic material deposited and buried in the earth millions of years ago. Natural gas is converted into liquid form (Liquified Natural Gas or LNG) in order to storage or transport. Sri Lanka is planning on building LNG terminals to import natural gas in the form of LNG. Table 3.3 provides specifications of natural gas available in the North America. With the expectation of quality of natural gas used in Sri Lanka to be similar to that of other major natural gas using countries, the values given in Table 3.3 can be assumed to reflect the specifications of natural gas that would be used in Sri Lankan gas power plants in the future.

Table 3.3: Specifications of Natural Gas

Characteristic	Unit	Limit
Upper heating capacity	kJ/m^3	35,000-42,000
Wobbe Index	kJ/m^3	46,500-52,500
Methane, min	% Vol	86.0
Ethane, max	% Vol	10.0
Propane, max	% Vol	3.0
Butane and heavier, max	% Vol	1.5
Oxygen, max	% Vol	0.5
Inert ($N2+CO_2$), max	% Vol	4.0
Nitrogen	% Vol	2.0
Total Sulphur, max	mg/m^3	70
Hydro sulphuric gas (H_2S), max	mg/m^3	10.0
Dew point of water at atm, max	°C	-45

Source: North American Energy Standards Board (https://www.naesb.org/pdf2/wgq_bps100605w2.pdf).

3.1.3 Heavy Fuel Oil

Table 3.4 lists the specifications of fuel used in Sri Lankan HFO based power plants. However, the Yugadhanavi combined cycle power plant uses a specific type of HFO in which the sulphur content is very low (less than 1%).

Table 3.4: Specifications of HFO used in Sri Lankan Power Plants

Property/Test	Test (IP)	Method (ASTM-D)	Specification
Density @15 °C kg/m^3	160	1,298	Max 970
Flash Point (PMCC) °C (°F)	34	93	Min 60 (Min 140)
Pour Point °C (°F)	15	97	Max 21.1(70)
Sulphur Content % (w/w)	61	129 or 1,552	Max 3.5
Redwood 1 @100 °F Sec (Note 1)			Max 1,500

Viscosity Kinematic @ 50°C (112°F)	71	445	Report
Water content % (v/v)	74	95	Max 1.0
Ash % wt.	4	482	Max 0.2
Conradson Carbon % w/w		189	Max 12
Sediment by Extraction ppm	53	473	Max 0.25
Caloric Value (gross) kcal/kg	12	240	Min 10,200
Strong Acid No. KOH mg/g	1	974	Nil
Metal Contaminants		3,605	Max 200 ppm
V		3,605	Max 200 ppm
Na + K		3,605	Report
Ca		3,605	Report
Pb		3,605	Report

Source: Ceylon Petroleum Corporation (http://ceypetco.gov.lk/import-products/)

3.1.4 Diesel

Table 3.5 lists the specifications of fuel used in Sri Lankan diesel power plants.

Table 3.5: Specifications of Diesel used in Sri Lankan Power Plants

Property/Test	Method (ASTM-D)	Specification
Appearance		Clear & free from water and impurities
Density @15^{0}C kg/m^3	1298/4052	820 – 860
Colour ASTM	1,500	Max 2.0
Distillation	86	
IBP ^{0}C		Report
T10 ^{0}C		Report
T50 ^{0}C		Report
T90 ^{0}C		Max 370
Recovery @ 315^{0}C		Min 50
Recovery @ 350^{0}C		Min 80
Cetane Index or	976	Min 45
Cetane Number	613	Min 49
CFPP ^{0}C		Max 10
Sulphur Content mg/kg	4,294	Max 3,000
Flash Point ^{0}C	93	Min 60
Viscosity Kin @37.8 ^{0}C cst	445	1.5 -5.0
Water Content mg/kg	95	Max 500
Cu Strip corrosion 3 hrs @ 50 ^{0}C	130	Max 1
Ash % m/m	482	Max 0.02
Carbon residue % m/m	524/4530	Max 0.3
Total Acid No. mg KOH/g	974/664	Max 0.2
Caloric value gross kcal/kg	240	Min 10,500
Appearance		Clear & free from water and impurities

Source: Ceylon Petroleum Corporation (http://ceypetco.gov.lk/import-products/)

3.2 Thermal Power Generation Technologies

In construction of thermal power plants, many kinds of elemental technologies are concerned. They can be varied according to the fuel used and type of prime mover technology used.

A list of fossil-fuel based grid connected thermal power plants in Sri Lanka is given in Table 3.6.

Table 3.6: List of Thermal Power Plants in Sri Lanka

Thermal Power Plant	Capacity (MW)	Year of Commission	Type of Fuel	Technology
CEB, Kelanitissa GTs	80	1981	Diesel	Open cycle gas turbine
CEB, Sapugaskanda A	80	1984	HFO	Diesel engine
CEB, Sapugaskanda B	80	1997	HFO	Diesel engine
CEB, Kelanitissa GT7	110	1997	Diesel	Open cycle gas turbine
CEB, Barge mounted	51	1998	Residual Oil	Diesel engine
CEB, Kelanitissa CCY	165	2001	Diesel	Combine cycle gas turbine
Sojitz, Kelanitissa	163	2003	Diesel	Combine cycle gas turbine
ACE Power, Embilipitiya	100	2005	HFO	Diesel engine
Yugadhanavi, Kerawalapitiya	270	2008	HFO	Combine cycle gas turbine
Lak Vijaya, Norochcholai	900	2011	Coal	Steam turbine
Uthuru Janani, Chunnakam	24	2014	HFO	Diesel engine

3.3 Pollution by Different Types of Thermal Power Plants

There are various types of gaseous, liquid, and solid pollutants emitted during a life-cycle of a thermal power plant. These pollutants are created by various processes involved in the conversion technology used by each power plant. However, the most significant process in relation to environment pollution is the fuel combustion process, which produces different types of air pollutants and leaves behind solid waste such as ash and fuel residue.

The qualitative and quantitative characteristics of pollutants depend on many factors including the technology, fuel type, fuel quality, capacity, age of the plant, operational procedures & level of maintenance, types of emission control technologies adopted, and operational conditions of the emission control technologies. Further, the impacts of these pollutants are primarily determined by their contribution to the ambient concentrations and depositions in air, water, soil, and other elements in the biosphere. The ambient concentrations and depositions of pollutants are determined by not only the emission from the sources, but also the characteristics of dispersion through air, water, and soil, which in turn affected by weather conditions and climate.

3.3.1 Pollution by Steam Power Plants using Coal

Emission levels of coal power plants in operation (i.e. LVPP) and expected to be operated in Sri Lanka is given in Table 4.1.

Table 4.7: Pollutants Emitted by Coal Power Plants

Pollutant	LVPP (kg/MWh)	CEB Planned (kg/MWh)
SO_x	1.872	0.126
NO_x	0.922	0.504
Carbon dioxide (CO_2)	340.6	340.6
PM	0.124	0.025
Mercury (Hg)	N/A	N/A
Fugitive emissions	N/A	N/A

N/A = Not Available.

Sources: Environmental Impact Assessment (EIA) of Lak Vijaya Power Plant; Long Term Generation Expansion Plan of CEB [1].

3.3.2 Pollution by Combined Cycle Power Plants using Natural Gas

Sri Lanka currently does not have any combined cycle power plants running on natural gas. However, CEB is planning on constructing natural gas based combined cycle power plants and to import LNG to be regasified and used at the power plants. Table 4.2 gives the assumed pollutant levels of these power plants planned by the CEB.

Table 4.8: Pollutants Emitted by Combined Cycle Power Plants using Natural Gas

Pollutant	Emission factor (kg/MWh)
SO_x	0.00
NO_x	0.20
CO_2	421

Source: Long Term Generation Expansion Plan of CEB [1].

3.3.3 Pollution by Combined Cycle Power Plants using Diesel

Sri Lanka currently operates two combined cycle power plants running on diesel and Table 4.3 provides the emission levels of this type of power plants.

Table 4.9: Pollutants Emitted by Diesel based Combined Cycle Power Plants

Pollutant	Emission factor (kg/MWh)
SO_x	1.631
NO_x	1.008
CO_2	266.7
PM	0.018

Source: Long Term Generation Expansion Plan of CEB [1].

3.3.4 Pollution by Diesel Engine Power Plants using Heavy Fuel Oil

As a short term measure, reciprocating engine (diesel engine) based power plants are also to be used in the Sri Lankan power system, in addition to existing power plants owned and operated by the CEB and a few Independent Power Producers (IPPs). Their emission levels are provided in Table 4.4.

Table 4.10: Pollutants Emitted by HFO based Diesel Engine Power Plants

Pollutant	Emission factor (kg/MWh)
SO_x	6.152
NO_x	4.320
CO_2	274.7
PM	0.046

Source: Long Term Generation Expansion Plan of CEB [1].

4 ADVERSE IMPACTS OF THERMAL POWER GENERATION

4.1 Causes of Adverse Impacts by Thermal Power Generation

The following are some of the issues related to thermal power generation, which can result in externalities:

- Release of CO_2, SOx, NOx, PM, and heavy metals including Hg as a result of fuel combustion,
- Withdrawal of large volumes of water from ground or from water bodies,
- Discharge of hot water and effluents to nearby water bodies, directly affecting the flora and fauna in them,
- Fugitive emissions from fuel storage such as coal yards, oil storage etc.,
- Disposal of ultimate waste such as ash (both bottom ash and fly ash), used lubricants etc. from thermal power plants,
- Spillage and dispersion of fuel materials during unloading, transporting, storing, and handling, and
- Disposal of end of pipe waste such as scrubber effluent etc.

Following are some of the key impacts linked with the above issues:

- Increasing human mortality due to exposure to pollutants,
- Increasing human morbidity due to exposure to pollutants including respiratory, cardio, renal, dermatological, neural, digestion and reproductive systems and there resulting social and national productivity losses,
- Increasing negative health Impacts on women, children, and elderly,
- Increasing birth related health issues,
- Marine and terrestrial eco-toxicity and its impacts on general ecology as well as human,
- Property damage due to acidification,
- Impact on agriculture,
- Impact on sensitive ecosystems such as coral reefs, wetlands etc.,
- Contribution to impact due to global warming,
- Loss of livelihood due to above impacts,
- Changes to beach profile in a form of sand accretion (positive) or erosion (negative),
- Loss or change in biodiversity in affected areas over a period,
- Bio-magnification of heavy metals and other toxins and possible impact on aquatic biota and human impact, and
- Possible colonization and spread of invasive species at the cooling water inlet, pipes etc., for occurrence of biofouling organisms and potential invasive species.

Most of the above would have negative economic effects, which can be identified as externalities of thermal power generation.

4.2 Health Impacts of Pollution by Thermal Power Generation

4.2.1 Direct Health Impacts of Thermal Power Generation

To identify the health impacts of thermal power generation, a desk review of studies done to assess mortality and morbidity on selected end points associated with targeted pollutants generated from coal and other fossil fuel-based power plants was carried out.

Burning of coal leads to the emission of hazardous gases with many underlying health impacts. In coal combustion, there is formation of CO_2 and carbon monoxide (CO), sulphur dioxide (SO_2) and sulphur trioxide (SO_3), and nitrogen dioxide (NO_2) and nitric oxide (NO) and particulate matter (PM). These have been correlated with many health problems directly and indirectly.

The interaction of CO_2 with particulate matter ($PM_{2.5}$), which thereby changes the air quality, leads to increased asthma attacks and other respiratory and cardiovascular diseases with underlying poor life expectancy rates. Inhaling PM may cause some dangerous diseases, including chronic obstructive pulmonary disease (COPD), stroke and lung cancer [2]. Fine PM, especially $PM_{2.5}$, is known to cause Ischaemic Heart Disease (IHD) including heart attacks, stroke, COPD, and lung cancer.

Particulates generated from coal power plants cause air pollution. A clear relationship between air pollution and developmental disorders, pregnancy outcomes, infant mortality and other genetic anomalies at both personalized and population levels have been shown.

PM_{10} and $PM_{2.5}$ include inhalable particles that are small enough to penetrate the thoracic region of the respiratory system. The health effects of inhalable PM are well documented. There is a close, quantitative relationship between exposure to high concentrations of small particulates (PM_{10} and $PM_{2.5}$) and increased mortality or morbidity, both daily and over time. These health effects include:

- Acute effects such as respiratory and cardiovascular morbidity, aggravation of asthma, respiratory symptoms, and an increase in hospital admissions,
- Mortality due to IHD, stroke, lung cancer and COPD as chronic health issues.

Susceptible groups with pre-existing lung or heart diseases, as well as elderly people and children, are particularly vulnerable. For example, exposure to PM affects lung development in children, including reversible deficits in lung function as well as chronically reduced lung growth rate and a deficit in long-term lung function [3]. Exposure to particulate pollution during very young age has shown to increase the risk of developing stroke, heart diseases, lung cancer and chronic lung diseases in adulthood in children.

Small particulate pollution has health impacts even at very low concentrations – insofar no threshold has been identified, below which, no damage to health is observed.

The formation of the poisonous SO_2 gas, a major pollutant in air, may accelerate the rate of diseases and decrease life expectancy in the vicinity of power plants [4]. SO_2 can affect the respiratory system and the functions of the lungs and cause irritation of the eyes. Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more prone to infections of the respiratory tract. Hospital admissions for cardiac disease and mortality increase on days with higher SO_2 levels. When SO_2 combines with water, it forms sulphuric acid, which is the main component of acid rain: a cause of deforestation.

In addition, high levels of NO_2 in the air causes a reduction in the pulmonary function in humans [5], asthma attacks and genetic mutations [6]. PM level, individually and in combination with NO_2 in air, leads to the development of serious diseases, including lung cancer, cardiovascular diseases and reproductive disorders [7]. The ozone gas (O_3) formed as a result of NO_2 reaction with the volatile organic compounds in the air causes ozone-related asthma exacerbations in infants [8].The interaction of PM with DNA leads to the formation of DNA adducts impairing neurodevelopment, intelligence quotient (IQ) levels and intelligence in children [9].

4.2.1.1 Mortality Related to Selected Air Pollutants Generated by Thermal Power Plants

For a given power plant or a type of power generation, assessment of health impacts, especially from air pollutants can be performed at two levels:

1. Qualitative assessment: can be done by conducting focus group discussions with key informants and general public and describe mortality patterns.
2. Quantitative assessment: can be done by estimating the mortality of selected end points using already calculated Attributable Risk Fractions (ARF) relevant to Sri Lanka

4.2.1.2 Morbidity Related to Selected Pollutants Generated by Thermal Power Plants

This too can be done at different levels.

1. Qualitative assessment: by key informant interviews and focus group discussions
2. Quantitative assessment: by comparative cross sectional surveys to generate primary data and using secondary data.

A cross-sectional survey can be done at the site as well at a comparative site to look for significant increases in selected health outcomes. However, the surveys could not be commissioned in the present study due to lack of corporation received to from the power plants selected as case studies.

Alternatively, several studies have been carried out to identify the morbidity and mortality endpoints which are related with key air pollutants. Table 4.5 presents the specific morbidity and mortality endpoints considered in this report for calculation of disease or mortality attributable to the pollutants released from thermal power plants. Due to unavailability of Dose Response Functions (DRFs) for other reproductive and dermatological end points for Asian region, those have not been considered in this table.

Table 4.1: Health Endpoints Associated with Air Pollutants

Outcome	Disease	Pollutant
Mortality	Respiratory diseases Cardiovascular disease COPD (Chronic-obstructive pulmonary disease) Cerebrovascular events Ischemic heart disease Lung cancer	Particulate matter (PM_{10}, $PM_{2.5}$) NO_x SO_x CO O_3 (formed from SO_x and VOC)
Hospital Admissions	Respiratory diseases (acute and chronic) COPD Cardiovascular disease Cerebrovascular events Chronic bronchitis Asthma Lower respiratory symptoms	Particulate matter (TPS, PM_{10}, $PM_{2.5}$) NO_x SO_x CO O_3 (formed from SO_x and VOC)
Restricted Activity Days		PM

Sources: [10], [11].

Dose Response Function (DRF) is used to quantify the functional relationship with health impact and air pollution. The DRF can be presented as $Y = f_{impact}\,(X)$ where Y is the effect of a pollution level of X and X is accrual dose which is absorbed by the receptor (human).

The Health Effects Institute (HEI) has carried out several research studies to quantify the functional relationship between Y (effect) and X (dose). Based on the research studies, Table 4.6 presents summary of estimates of percentage change in mortality outcomes and Table 4.7 presents summary of estimates of percentage change in morbidity outcomes. These are the most reliable available data to calculate the health impact in Asian region. These values are based on an increment of 10μg/m^3 of ambient pollutant concentration at a given point per day.

Table 4.2: Change in Mortality Outcomes due to Ambient Pollution

Mortality Causes	Percentage Increase per 10µg/m³ Increase	
	Average	95% Confidence Interval
PM_{10}		
All causes, all ages	0.27	0.12 to 0.42
All causes, >=65	0.45	0.29 to 0.61
Respiratory, all ages	0.86	0.34 to 1.39
Respiratory, >=65	1.09	0.55 to 1.63
Cardiovascular, all ages	0.36	0.09 to 0.62
Cardiovascular, >=65	0.53	0.53 to 0.75
NO_2		
All causes, all ages	0.98	0.54 to 1.42
Respiratory, all ages	1.74	0.85 to 2.63
Cardiovascular, all ages	1.08	0.59 to 1.56
SO_2		
All causes, all ages	0.68	0.40 to 0.95
Respiratory, all ages	1.00	0.60 to 1.40
Cardiovascular, all ages	0.95	0.30 to 1.60
COPD, all ages	1.72	0.10 to 3.36

Table 4.3: Change in Morbidity Outcomes due to Ambient Pollution

Health End Point	Percentage Increase per 10µg/m³ increase	
	Average	95% Confidence Interval
PM_{10}		
RHA – all respiratory causes	1.3	0.2 to 2.2
RHA – asthma incidents	1.2	0.5 to 1.6
RHA – COPD	1.5	1.1 to 1.9
CVHA – All CVD	0.7	0.6 to 0.8
CVHA – Angina/Ischemic	0.7	-
Loss of work-days	31.5 days/1,000 adults/year	29 to 39 days/1,000 adults/year
NO_2		
RHA – All respiratory causes	0.92	0.17 to 1.68
CVHA – Angina/Ischemic	0.8	0.0 to 1.2
SO_2		
RHA – All respiratory causes	0.51	0.17 to 1.19
RHA – Asthma incidents	1.4	1.1 to 1.7

RHA = Respiratory Hospital Admissions; CVHA = Cardiovascular Hospital Admissions.

These DRFs have been calculated for the Asian Region. However, it has since been identified that $PM_{2.5}$ gives rise to more adverse health outcomes. RDFs of $PM_{2.5}$ for the Asian region could not be found. Therefore, in future, it is required to do a comprehensive study to identify other health end points attributable to air pollutants released in the process of power generation. For reference, the association between $PM_{2.5}$ and mortality for a stratum of 8,096 participants and certain sub-populations estimated by a study conducted in the USA is given in Table 4.8.

Table 4.4: Change in Mortality/Morbidity Outcomes due to $PM_{2.5}$

Mortality/Health End Point	Percentage Increase per 10µg/m³ Increase	
	Average	95% Confidence Interval
Mortality		
All causes	1.14	1.07 to 1.22
Chronic conditions		
Hypertension	1.17	1.03 to 1.32
COPD	1.09	0.95 to 1.26
Diabetes	1.04	0.85 to 1.27

Source: Harvard Six Cities Study (1974–2009)

However, using above DRFs, effects on mortality and morbidity due to important end points cannot be calculated due to non-availability of incremental increase of PM2.5 concentration in LVPP

4.2.2 Indirect Health Impacts due to Climate Change

The emission of greenhouse gasses (particularly CO_2) from coal power generation will contribute to global warming. Global warming will result in more natural disaster related deaths and illnesses among humans. Vector borne diseases such as malaria and dengue, water borne diseases and food borne diseases are predicted to increase with climate change. Food and water shortages will affect the health of humans, especially the pregnant mothers and children at large. Heat related adverse health outcomes too are predicted to increase and children and old age people will be more vulnerable to such adverse health outcomes. Climate change will increase cardiovascular and respiratory diseases among humans. Environmental refugees will increase with predicted adverse mental health outcomes.

4.2.3 Occupational Exposures and Health of Workers

Since the workers are exposed especially to high noise and PM, they are at a higher risk of developing hearing loss, wheezing, heart diseases, allergies, skin diseases, chronic lung diseases and even lung cancer. Any assessment on health impacts of coal power plants should consider occupational exposures and associated health impacts of workers too.

4.2.4 Impact of Heavy Metal Contamination

Post-combustion waste generated by the coal power plants in the form of fly ash, bottom ash and slag could contain heavy metals such as Hg and arsenic (As). The ash containing heavy metals can contaminate water and the food web and get consumed by humans and other phytoplankton and zooplankton.

4.2.4.1 Mercury

During coal combustion, Mercury (Hg) exits in three major forms: oxidized Hg^{2+}, particle-bounded Hg and elemental form Hg^0. A portion of Hg is converted into methyl mercury (MeHg) by microorganisms, particularly by bacteria in water. Seafood transfers this MeHg to human and mammals where it accumulates in the fetus of pregnant women and causes adverse effects on brain functioning as a neurotoxin.

Additionally, MeHg bio-accumulates through the food chain, and exerts its noxious effects on various organs including cardiac tissue, the liver and the kidney [12]. Neurotoxins affect the central nervous system (CNS) and cause neurological diseases in newborn and teenagers. During the early developmental stage of teenagers, MeHg causes some critical processes, causing irreversible brain damage [13].

When women have high exposure to MeHg during pregnancy, MeHg crosses the incomplete blood barriers of the fetus and enters the brain of the fetus, resulting in brain deformities in newborn. Such children have physical as well as mental subnormal development.

4.2.4.2 Arsenic

Arsenic (As) is the third most dangerous poisonous heavy metal present in coal fly ash. Thereby, the health impact of As heavily depends on its chemical form.

Owing to the ingestion of As within contaminated food, the symptoms of acute toxicity can set in within a short period of time. Some of these symptoms include weakness with flushing skin and muscular pain and/or abdominal pain, vomiting and nausea, colicky, and profuse diarrhoea. Furthermore, in many cases, skin becomes cold and sweaty, and decreased renal failure and lower urine concentration. Fatigue and drowsiness were often seen along with the development of psychosis which was manifested by paranoid delusions and delirium. Finally, shock may lead to seizures, a coma or death [14]. The human respiratory system can be affected due to inhalation through air dust and leads to asthma and other respiratory diseases. In addition, the consumption of As occurs through contaminated land and/or seafood and leads to serious issues in the human cardiovascular system. Long or short term exposure to As produces haemolytic or cytotoxic effects on red blood cells, white blood cell and platelets, and causes a wide range of blood diseases. For instance, anaemia and lowered white cell counts are caused by chronic oral exposure to As [15]. Moreover, relatively high doses of this poisonous element cause bone marrow depression in humans. In addition, potential damage in DNA induces mutations in a wide variety of genes, resulting in a wide range of cancers [16], including skin cancer, respiratory cancer, and leukaemia through the consumption of water and air, contaminated with As. Thus, As released from a coal power plant, leads to many serious skin, heart, blood, brain, and lung diseases.

4.2.5 Fly Ash and Radionuclides

Like other trace elements, coal also contains some radioactive elements. During coal combustion, exposure to these radionuclides, has severe health impacts including bone damage, kidney damage and cancers [17].

4.2.6 Overall Health Impact

In coal combustion based power generation, the emission of COx, NOx, SOx, PM and some heavy metal pollutants are known to induce a wide range of health problems. As a result of coal processing, COx is a major contributor to global warming and some diseases including COPD and lung cancers. Uncontrolled emission of SO_2 within SOx, causes a wide range of diseases including destabilization of the heartbeat, skin cancer, asthma, and cough, headache, throat, and nose irritations. NOx, another major pollutant from energy production coal power plant, is causing hypoxic respiratory failure mainly related to persistent pulmonary hypertension of newborn (PPHN).

Collectively, COx, SOx and NOx have not only direct health impacts, but indirect impacts damaging the global food web due to acid rains. PM, along with COx, SOx and NOx are damaging both the environment and human health on a large scale. Heavy metal traces produced in coal combustion plants are also causing serious diseases, such as skin and lung cancer, cardiovascular diseases, abdominal pain, gene mutation, leukaemia and comas resulting in death (Table 4.9). For instance, the chemical reaction of NO_2 with organic pollutants and $PM_{2.5}$ is leading to severe health problems, including asthma, chronic obstructive pulmonary disease (COPD) and cardiac arrhythmias in adults, and higher rates of mortality in infants.

Table 4.5: Health Impacts of Heavy Metals in Coal Combustion Process

Trace elements	Health impacts
Lead (Pb)	Hyperactivity and aggression in children. High blood pressure. Kidney failure. Cardiovascular diseases Premature delivery or miscarriages in pregnancy.
Arsenic (As)	Respiratory diseases. Cardiovascular disease. Anaemia and leukopenia Genes mutation Skin and lungs cancer

Trace elements	Health impacts
	Abdominal pain Coma
Mercury (Hg)	Affect liver, kidney, and cardiac tissue. Neurological diseases. Brain damage in new-born babies.
Cadmium (Cd)	Bronchial and pulmonary irritation, long-lasting impairment of lung function, and renal damage This a known human carcinogen
Antimony (Sb)	Gastrointestinal symptoms (vomiting, diarrhoea, abdominal pain, and ulcers) Haemolysis with abdominal and back pain
Barium (Ba)	Vomiting, perioral paresthesias, diarrhoea, paralysis, hypertension, and cardiac dysrhythmias
Chromium (Cr)	High exposure to chromium VI may result in damage to the kidneys, gastrointestinal bleeding, and internal bleeding This is a known human carcinogen
Selenium (Se)	Short-term oral exposure to high concentrations of selenium may cause nausea, vomiting, and diarrhoea. Chronic oral exposure to high concentrations of selenium compounds can produce a disease called selenosis. The major signs of selenosis are hair loss, nail brittleness, and neurological abnormalities (such as numbness and other odd sensations in the extremities). Brief exposures to high levels of elemental selenium or selenium dioxide in air can result in respiratory tract irritation, bronchitis, difficulty breathing, and stomach pains. Long term exposure to either of these air-borne forms can cause respiratory irritation, bronchial spasms, and coughing.
Nickel (Ni)	Skin rash, eczema, asthma attacks, chronic bronchitis, reduced lung function, lung, and nasal sinus cancer

5 VALUATION OF EXTERNALITIES OF THERMAL POWER GENERATION

5.1 Estimation of GHG Related Global Externality Cost of Thermal Power Plants

In the calculation of the damage cost due to GHG emissions, given the global nature of the damage, estimates available from other countries can be adopted using the benefit transfer approach.

5.1.1 Calculation of Externality Cost of CO_2 Emissions

United States Environmental Protection Agency (USEAP) provides a reasonable estimate for externality cost of CO_2, which is a measure of the long-term damage done by a ton of CO_2 emissions within a year. The externality cost of CO_2 is meant to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as increased costs for air conditioning [18]. The fifth assessment report (AR5) of the International Panel on Climate Change (IPCC) has observed that the estimates on externalities of CO_2 emissions omit various impacts that would likely increase societal damages. The models used to estimate the social cost of CO_2, known as integrated assessment models, do not currently include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature because of a lack of precise information on the nature of damages and because the science incorporated into these models naturally lags behind the most recent research. Nonetheless, the current estimates of the externality cost of CO_2 are a useful measure to assess the climate impacts of CO_2 emission changes. Therefore, this study follows the recommended values as the best available information on CO_2 emissions by thermal power plants.

5.1.2 Calculation of Externality Cost of CH_4 and N_2O Emissions

Externality costs of methane (CH_4) and nitrous oxide (N_2O) are estimated based on estimates made on Marten et al. (2015a and 2015b)[1]. The externality cost estimates of CH_4 and N_2O emissions are consistent with the modelling assumptions that have been made in estimating the externality cost of CO_2 emissions discussed in Section 5.1.1. Methodology for valuing the externalities of CH_4 and N_2O emissions and their suitability for application on regulatory decision making have been subject to rigorous reviewed internationally. Thus, the same estimates have been used in this study, following the benefit transfer approach.

5.2 Estimation of Local Externality Cost of Thermal Power Plants

5.2.1 Estimation of Health Damage Costs Due to Air, Water, and Land Pollution

Among all externalities caused by thermal power plants, adverse health effects are of special importance. The extent of the health effects depends on the magnitude and duration of the exposure to specific pollutants, and the nature of the exposed population.

5.2.1.1 Value of a Human Life

In the public policy domain, any human life lost is considered an economic loss to the country as the potential contribution to the economic output of the country by that person over his/her remaining life ceases with the death of that person [19]. Although human life cannot be valued in monetary terms, to assist in policy decisions, a value for a life is calculated purely based on

[1] The SC-CH_4 and SC-N2O estimates are consistent with the modelling assumptions underlying the SC-CO_2 estimates. Both the methodology for valuing the damages from CH4 and N2O emissions and the application of the SC-CH_4 and SC-N_2O estimates to regulatory cost-benefit analysis have been subject to rigorous independent peer review and public comment within USA (US EPA, 2016)

selected statistical parameters and the economic value so assigned to a human life is termed the 'value of statistical life'. Value of statistical life (VSL) depends on the level of development and quality of life of the country as well as the life expectancy of the citizens of that country.

The economic cost of increased mortalities attributed to a power plant can be valued by multiplying the increase in annual mortalities due to the power plant by the VSL. Similarly, the economic impact of increased illnesses can be valued by multiplying the increase in morbidity rate due to the power plant by the average Cost of Illness (COI) of the country. Summation of the cost of mortality and the cost of morbidity gives the health cost due to pollution by the power plant.

5.2.1.2 Human Capital Approach/Cost of Illness Approach

When a person is ill, his/her ability to contribute to the economic output is reduced or temporarily halted. At the same time, medication and other treatment causes additional costs to the economy. Cost of Illness estimates external costs through changes in private and public expenditure on medical commodities and earnings lost due to days not worked resulting from the suffering from various impacts related to noxious facilities. There are two types of costs: direct costs and indirect costs. Direct costs measure the resources used to treat an illness while indirect costs measure lost productivity such as the effects of the illness on the ability of either patients or their care givers to work (e.g. lost income) or engage in other activities (e.g., cleaning the house).

5.2.1.3 Fulfilment of Data Requirement: Household Survey

A pre-tested questionnaire shall be used to collect data from the surrounding households. The questionnaire shall contain the individual level information regarding health impacts due to the power plant which may include the following information:

- Type and the frequency of the illness,
- Cause of the illness identified by the doctor/ medical tests
- Mode of obtaining medical advice (either government or private),
- Mode of transportation and the respective costs,
- Distance to the medical centre,
- Time spent on visit (both on transport and waiting times),
- Medical fees including doctors' fees and cost of test and medicine,
- Duration stayed at hospital and home,
- Information of the caretaker/costs,
- Information about any deceased family members,
- Household willingness to pay to avoid any health impacts.

This method can be used to estimate the damages caused by air pollutants released as a result of fuel combustion including SOx, NOx, and PM and heavy metal pollution of air and water including mercury compounds. In addition, this method can be used to estimate damages due to fugitive emissions from fuel storage such as coal yards, oil storage and fly ash disposal mechanisms, costs of contaminating ground water, sea water and soil through the toxic materials contained in ash and other discharges.

5.2.2 Estimation of Costs of Mitigative Measures by the Households

Estimation Methodology: Averting Behaviour Method/Preventive/Mitigative Expenditure Method

The preventive expenditure method is a cost-based valuation method that uses data on actual expenditure made to alleviate all environmental impacts. In case of power plants, the averting or mitigating behaviour method infers a monetary value for some environmental externalities by observing the costs people are prepared to incur in order to avoid any negative effects from those externalities.

These methods assess the value of non-marketed commodities such as cleaner air and water, through the amount individuals are willing to pay for market goods and services to mitigate an environmental externality, or to prevent a utility loss from environmental degradation, or to change their behaviour to acquire greater environmental quality.

This method can be used to estimate damages due to fugitive emissions from fuel storage such as coal yards, oil storage and fly ash disposal mechanisms, costs of contaminating ground water, sea water and soil through the toxic materials, contained in ash and other discharges.

5.2.3 Estimation of Lost Productive Time Due to Externalities

Estimation Methodology: Opportunity Cost Method

The opportunity cost method values the costs of environmental damage in terms of what is being foregone to achieve it. This method is used to enumerate the opportunity costs of foregone benefits associated with externalities posed by the power plants such as forgone benefit of clean groundwater due to water pollution and additional hours spent on cleaning due to dust, soot and other nuisances caused by the power plants which alternatively could have been used for other productive work.

Opportunity cost of lost productive time=∑ i=1 to N [$d \times f \times h \times 48$]

Where; N is the number of individuals involved in cleaning, d is the no of days of cleaning by an individual per week (Days), f is the time spent on a day for additional work-cleaning and waiting time (hours per day), h is the hourly wage rate.

This method can be used to estimate damages due to fugitive emissions from fuel storage such as coal yards, oil storage and fly ash disposal mechanisms.

5.2.4 Estimation of Damages Caused to Natural Habitats

Estimation Methodology: Clean-Up Cost Method /Replacement Cost Method

This assumes that once the damage resulting from pollution is done, the costs of rehabilitation to achieve the pre-damage situation appear as a (minimum) proxy economic value of damage done. The damages to natural environments such as, wetlands, ocean habitats could be valued using this method.

Replacement cost method uses the cost of replacing or restoring a damaged asset to its original state as the measure of the benefit of restoration and thus as the cost of damage. The technique can be used to estimate the damage due to contaminated ground water, sea water and soil through the toxic materials contained in ash and other discharges

5.2.5 Estimation of Costs on Agricultural Crops/Fishery

Estimation Methodology: Effect on Production Method

This method is based on a linkage between a change in the state of the environment and ultimately a change in good or service that is traded in the market and therefore has an observable price. The physical linkage is typically described by a cause-effect relationship which links for example, the level of water pollution (cause) to a change in harvest rates (effect). The expected change in the quantity of fish harvested is then converted into monetary units using the prevailing market prices. This method can be used to measure the impact of power plants on agricultural crops and fishery.

6 POLLUTION CONTROL TECHNOLOGY SELECTION

6.1 Introduction

Pollution control refers to the various measures taken to meet certain emission standards introduced to mitigate adverse impacts on human health and environment. These techniques include changes in processes or raw materials, modification of equipment and installation of devices at the end process equipment to treat the effluents. The environmental performance of a new or existing power plant could be evaluated based on the pollution control technologies incorporated and their operating characteristics. Further, comparison with the best available technologies (BATs) or best available retrofit technologies (BARTs) would allow to establish the potential for further improvements in the environmental performances, with emphasis on the main compliance options available to satisfy regulatory requirements. Ideally, the use of BATs for pollution control has to be considered at the design stage of the whole power plant, since these sub-systems are integral parts of a complex system as a whole and there are interdependencies providing multiple options to achieve same level of compliance. Thus, for an existing power plant, use of certain BATs/BARTs will have limitations due to the need of significant changes in the system components.

Another important aspect is that the use of BATs/BARTs certainly demands for best operational performance of power plants. Failure in such operations is not acceptable and should be corrected as a mandatory requirement. Hence, changing the emission control technology to cover up the deficiencies in operations could not be considered as a BAT/BART option.

It should be noted that the objective of this chapter to quantify the financial implications of the use of BATs/BARTs available at commercial level, which is not necessarily leads to zero emissions. Accordingly, there would be certain level of emissions, and the emission standards are set by considering the practical achievability. If a technology cannot achieve the set standards, the practical intervention is to ban the use of it, rather than estimating a cost. The concept of zero emission coal plant is still a hypothetical scenario and there is no validated data on cost of such emission control technologies applicable for any power plants including coal-fired. Further, the identification of the best emission control option/s may require detailed modelling and technical assessments of the designs, which is beyond the scope of this study. The analysis here is practically limited to the BATs/BARTs available in the commercial level with established technical and financial performance characteristics.

6.2 Pollution Control Technologies

The main source of pollution of any thermal power plant is the combustion of fuel. The main air pollutants of fossil fuel combustion include; SO_2 and NOx, PM, and Hazardous Air Pollutants (HAPs), such as Hg, Cr, Pb and As; acid gases, such as hydrogen chloride and hydrogen fluoride; dioxins and furans; and other toxic air emissions. Modern pollution control systems are capable of dramatically reducing air pollution emissions from power plants. A wide variety of pollution control technology solutions are available to cost-effectively control air pollution emissions from thermal power plants, and many technologies can reduce more than one type of pollutant, as illustrated in the following table:

Table 6.1: Pollution Control Technology Solutions

Control Technique	Pollutant					
	SO_2	NO_X	Hg	HCl	PM	Dioxin / Furan
Combustion controls	N	Y	C	N	N	Y
Selective Non-Catalytic Reduction (SNCR)	N	Y	N	N	N	N
Selective Catalytic Reduction (SCR)	N	Y	C	N	N	C
PM controls (such as ESP and baghouse)	N	N	C	N	Y	C
Low sulphur fuel	Y	C	N	C	N	N
Dry scrubber	Y	N	C	Y	C	N
Wet scrubber	Y	N	C	Y	C	N
Dry sorbent injection (DSI)	Y	C	C	Y	N	C
Activated carbon injection (ACI)	N	N	Y	N	N	Y

N = Technology has little or no emission reduction effect

Y = Technology reduces emissions

C = Technology is normally used for other pollutants but has a co-benefit emission reduction effect.

In the case of fugitive emission from fuel transport, storage, and handling, is very site specific and situational dependent, thus usually needs combination of specific control mechanisms and technologies. In particular, the dust emissions from coal yards and ash storage facilities in coal power plants could be controlled by the use of wind fences, water misters and/or chemical dust suppressants

6.3 Best Available Technologies for Pollution Control

The power plants have a range of available technology options as well as experience in their installation and operation that will enable the sector to comply with the emission standards. From an environmental perspective, the best option is the one that minimizes the total emission levels of the pollutant considered. However, use of the most effective pollution control option is not always feasible because of the economic, energy, environmental or technical impacts that it might impose. The BATs/BARTs thus cover not only the emission levels and other environmental performance of techniques but also the standards/guidelines for how the technology is used and the way in which the installation is designed, built, maintained, operated and decommissioned for high level of protection of the environment as a whole under economically and technically viable conditions. Accordingly, following top-down process could be used to determine BATs/BARTs for each specific power plant.

Step 1: Determine Characteristics of the Source and Evaluation Criteria

The technical and economic characteristics of the power plant in consideration must be defined accurately for the identification of BATs/BARTs for emission control. Technical criteria are primarily used to determine the potential emissions, emission control equipment effectiveness and equipment sizes. The technical evaluation criteria include type of combustor, fuel rate, fuel analysis, emission rates (controlled / uncontrolled), flue gas flow rates, site-specific constraints, etc. The economic evaluation criteria are also important as they determine the practical feasibility of implementation of BATs/BARTs. These include initial cost, operation cost, fuel cost, capacity factor, energy cot, escalation rate, indirect cost factor, etc.

Step 2: Review Emission Standards

Next step is to review the emission standards (both source emissions and ambient air quality) for identification of applicable emission limits for the determination of lowest achievable emission rate (which represents the most stringent emissions limitation that is achieved in practice by a class or source category). This provides information on a range of control effectiveness that should be considered in the analysis. As the power plant in consideration should comply with not only the source emission standards but also ambient air quality standards, air pollution dispersion modelling has to be performed by considering all the potential sources in the affected area together with meteorological conditions like wind profile, temperature profile and stability of the atmosphere to establish the required level of control at the source.

Step 3: Identify Available Control Technologies
Available options are those control technologies or techniques with a practical potential for application to the emission unit and the pollutant under consideration. These include the application of processes, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques, for control of the affected pollutant. Further, these cover technologies used elsewhere in the world. Technologies required under lowest achievable emission rate must also be included as control alternative, which usually represent the top alternative.

Step 4: Screening of Options
Here the technical feasibility of control options is evaluated with respect to the plant-specific (or emission unit-specific) factors, and unfeasible ones are eliminated from further consideration in BAT/BART analysis. Demonstration that an option is not technically feasible should be clearly verified through analysis based on physical, chemical, and engineering principles, that technical difficulties would preclude the successful use of the control option.

Step 5: Ranking of Options
All remaining control alternatives not eliminated in Step 4 are ranked and listed in order of overall control effectiveness for the pollutant under review, with the most effective control alternative at the top. A list should be prepared for each pollutant and for each emission unit (or grouping of similar units) subject to a BAT/BART analysis. The list should present an array of control technology alternatives and should include the information such as: Percent emission reduction, Expected emission rates, Energy impacts, Environmental impacts, Economic impacts (cost effectiveness).

Step 6: Selection of Options
After identification of available and technically feasible control technology options, the associated energy, environmental, and economic factors are evaluated in order to arrive at the final level of control. At this point, the analysis presents the associated impacts of the control option in the listing. Both beneficial and adverse impacts should be discussed and, where possible, quantified. In general, the BAT/BART analysis should focus on the direct impact of the control alternative. The most effective control alternative that satisfy technical, environmental, economic criteria is selected as the BAT/BART.

Typical BAT/BART for selected pollutants are given in Table 6.2.

Table 6.2: Typical BAT/BART for Selected Pollutants

Pollutant	Control Technologies	Efficiency
SO_2	Wet Flue Gas Desulfurization (FGD)	90% – 98%
	Dry Flue Gas Desulfurization (FGD)	75% - 85%
	DSI	70% - 75%
NO_X	SCR	70% - 90%
	SNCR	30% - 50%
	Low-NOX burners	65% - 75%
Mercury	ACI	80% – 90%
Acid gas	DSI	90% – 98%
	Wet FGD	90% – 98%
	Dry FGD	75% - 85%
PM / Metallic Toxics	Electrostatic Precipitation (ESP)	90% – 99.9%
	Fabric Filter (Baghouse)	99% – 99.9%

6.4 Cost of Pollution Control

6.4.1 The Basis

The emission control technologies are inbuilt subsystems of power plants that are used to comply with applicable environmental regulations. In some instances, they need to be replaced or retrofitted due to either failure to achieve the design level of performances or introduction of more stringent environmental regulations. In any case, the inclusion of emission control technologies results in increase in initial and running cost of the power plant. The incremental cost due to the use of BATs of a new plant or BARTs for an existing plant could be taken to estimate the corresponding incremental cost of electricity, which represents the upper bound of the incremental cost of most environmentally sound technology with respect to the conventional plant (of the same energy conversion technology and fuel).

6.4.2 Cost of Emission Control Technologies in Coal Power Plant

A summary of pollutant, the control technology, and typical costs relevant to the coal power plant is presented in Table 6.3. The details of the estimation are presented in Annex 2.

Table 6.3: Typical Costs of BAT for Selected Pollutants of a Coal Power Plant

<table>
<tr><th rowspan="2">Pollutant</th><th rowspan="2" colspan="2">Description of Control Technologies</th><th colspan="3">Cost (US$/kW)</th></tr>
<tr><th>Capital</th><th>Annual O&M</th><th>Annual Levelized</th></tr>
<tr><td>SO_2 [20], [21], [22]</td><td colspan="2">Wet Flue Gas Desulfurization (FGD)
Efficiency = 95%; Operational life = 20 yrs.</td><td>490</td><td>22.5</td><td>34.08</td></tr>
<tr><td>NO_X [22], [23], [24], [25]</td><td colspan="2">Selective Catalytic Reduction (SCR)
Efficiency = 90%; Operational life = 20 yrs.</td><td>195</td><td>9.5</td><td>13.79</td></tr>
<tr><td>Mercury [22], [24], [26], [27]</td><td colspan="2">Standard Actuated Carbon Injection (ACI)
Efficiency = 90%; Operational life = 20 yrs.</td><td>21</td><td>0.3</td><td>1.18</td></tr>
<tr><td rowspan="2">PM [23], [28], [29], [30]</td><td colspan="2">Dry Electrostatic Precipitation (ESP)
Efficiency = 99%; Operational life = 20 yrs.</td><td>120</td><td>12.5</td><td>11.31</td></tr>
<tr><td colspan="2">Baghouse – Reverse air cleaned type
Efficiency = 99%; Operational life = 20 yrs.</td><td>78</td><td>30.0</td><td>16.65</td></tr>
<tr><td rowspan="2">Fugitive Emissions (Coal Yard) [31], [32], [33], [34]</td><td rowspan="2">Wind fencing + Water mist system
Efficiency = 94%,
Operational life = 10 yrs.</td><td>Wind fencing;
Efficiency = 70%</td><td>20.52</td><td>1.54</td><td>3.00</td></tr>
<tr><td>Water mist;
Efficiency = 80%</td><td>1.93</td><td>0.84</td><td>0.71</td></tr>
</table>

Table 6.4 presents the incremental cost of energy due to incorporation of BAT for air emission control of a coal power plant.

Table 6.4: Incremental Cost of Energy due to Emission Control

Pollutant	Total Generation (t/yr)	Amount Captured (t/yr)	Abatement Cost (US$/t)	Incremental Cost of Electricity (Rs./kWh)
SO_2	16,819	15,978	639.83	0.851
NO_X	6,240	5,616	736.64	0.344
Mercury	0.168	0.151	2,338,597.16	0.029
PM	116,052	114,892	43.48	0.416
Fugitive Emissions	54.45	51.18	21,745.50	0.093
Total Incremental Cost of Electricity				**1.733**

Note: (i) The PM control cost figures here refers to reverse air cleaned type baghouse. Those relevant to ESP technology are given in Annex 2.

(ii) Currency conversion rate: US$ 1 = Rs. 175

7 CASE STUDIES ON EXTERNALITY COST OF THERMAL POWER PLANTS

7.1 Case Study on Lak Vijaya Power Plant in Norochcholai

The Lak Vijaya Power Plant (LVPP), commonly known as the Norochcholai Coal Power Plant, is the largest thermal power station in Sri Lanka. The power station is in Norochcholai, Puttalam, towards the southern end of the Kalpitiya Peninsula in the North Western Province of Sri Lanka. Construction of the facility began in May 2006, with the first unit commissioning on 22 March 2011, adding 300 MW to the national grid. The US$ 455 million first phase generates about 1.7 TWh of electricity annually, which is a significant addition to the energy portfolio of the country, when compared with the total electricity production of 11.5 TWh in 2011.

Unit 2 and Unit 3 of LVPP started commercial operation in April 2014 and October 2014, respectively. Delay in constructing the power plant was due to protests launched by the communities and residents living near and around the project site. Each unit of LVPP produces electricity using a steam turbine, capable of generating 300 MW/unit, aggregating to 900 MW of generation capacity by the three units.

7.1.1 Operational Characteristics of Lak Vijaya Power Plant

LVPP uses bituminous coal as the primary fuel and auto diesel as the secondary (mainly during power plant start-ups). Lanka Coal Company (Pvt) Ltd. (LCC) procures coal on behalf of CEB, following the procurement procedures approved by the Ministry of Finance. Coal is usually imported from South Africa, Indonesia, Australia, and Russia under strict quality control measures enforced by CEB.

Currently, coal is brought to Sri Lanka via ships. The ships are anchored around 5 km from the shore and coal is delivered to the coal unloading jetty at LVPP using barges. Coal unloaded at the jetty is then transferred to the coal storage yard using coal conveyors. It is possible to store approximately 1.2 million tons of coal at the LVPP coal yard. Coal transportation and unloading is difficult during the Southwest monsoon (May to September). Therefore, coal required for this period is stored in the coal yard.

Moisture content of coal should be maintained at around 10% at the time of use. Furthermore, prior to being used, coal is pulverized to improve the combustion efficiency. For this purpose, there are five pulverizing mills installed and operated at the site. Pulverized coal is directed to the furnace of a steam boiler and burned inside each boiler furnace to get temperatures of above 1,200°C, which in turn, generate super steam in the boiler. 1,025 tons of water gets converted to super steam every hour. This steam is at a temperature and pressure of 541°C and 170 bar (16.7 MPa) respectively. Inside the turbine chamber, steam releases its energy to the blades of the steam turbine, which comprise high, intermediate, and low-pressure turbines, causing the rotor to rotate at 3,000 rpm. The turbine rotor drives the electrical generator coupled to the turbine to generate electricity through stator windings of the generator. The 20 kV generator connected to the turbine rotor produces 300 MW from each unit, collectively generating 900 MW from the three units. The power plant is connected to the national grid via two 220 kV double circuit transmission lines to Veyangoda and Anuradhapura grid substations, adding the largest amount of electrical energy to the national grid by a single power plant.

Power station flue gas is emitted through a 150 m tall chimney, one of the country's tallest man-made structures.

For various operational requirements, the power plant uses about 175,500 m^3/hour of water and sea water is used to meet this water requirement. Sea water is used mainly for three purposes:

- **Boiler feed water:** Sea water is sent through a demineralization process and used to produce steam in the boiler. During the demineralising process, conductivity of seawater is reduced from 100 000 μS/cm to 0.2 μS/cm. Water coming out of the boiler in the form of steam is cooled in a condenser and reused after polishing (removal of impurities such as silica) and de-aeration. About 300 m^3/hour of sea water is used to produce boiler make up & service water.
- **Condenser cooling water:** Major portion of the sea water intake is used for condenser cooling purposes. Sea water is filtered to remove macro particles prior to condenser feeding and Sodium Hypochlorite (NaOCl) is injected as chlorinating / disinfecting agent.
- **Desulphurization system:** Condenser cooing water is subsequently used in the gas scrubber for desulphurization of the flue gas. During this process, Sulphur and CO_2 are added to seawater, slightly increasing the acidity of sea water in comparison with the intake. However, as there is no Sulphur removal process from the effluent, it is expected for the seawater released from the power plant to have a higher Sulphur content.

On several occasions, condenser fouling and condenser tube damage had occurred at LVPP due to residual macro particles in condenser cooling water. Such damages result in cooling water and boiler feed water mixing together, leading to water contamination.

Gas scrubbers are installed at the stacks to minimize SO_2 emissions and to capture the fine particles escaping from the electro-static precipitator and sea water is used as scrubber medium. Scrubber outlet directly releases the used sea water back to the sea close to the shore.

Solid waste of the power plant is collected in two forms, namely fly ash and bottom ash. Bottom ash is continuously collected from the boiler beds and fly as is trapped through a set of electro-static precipitators (ESPs) fixed at the entry to the stacks. Collected ash is piled up close to the power plant. Water is sprayed over the ash piles to form a hard-scaly layer to prevent the ash dispersing under high winds. A steel barrier (wall) is being constructed as a windbreaker to reduce and redirect the wind flow from the sea-side to minimize coal dust dispersion.

7.1.2 Potential Impacts of Lak Vijaya Power Plant

Externalities of LVPP which could cause negative impacts on environment and society include the following:

1. GHG emissions,
2. Other gaseous emissions,
3. Resource depletion,
4. Thermal emissions,
5. Particulate emissions,
6. Fugitive emissions,
7. Heavy metal pollution,
8. Noise and vibration,
9. Water pollution.

The non-compliance of LVPP to some of the environmental regulations aggravate many of the above identified impacts. However, most of these non-compliance issues are currently being resolved. On the other hand, the relevant regulators have a duty towards the public to ensure the power plant is operating in accordance with the approvals granted to it. Any violation of performance requirements shall not be tolerated and shall not be considered the normal operation of the power plant for planning purposes. Thus, the externalities considered by this study are limited to emissions and pollution expected of the power plant upon LVPP meeting its specified operational performance levels.

7.1.2.1 GHG Emission

GHG emissions occur due to combustion of coal and diesel. These emissions are unavoidable due to the fixed composition of the fuels used, producing GHG when combusted. However, opportunities to improve power plant efficiency and process improvements to minimize plant stoppages/breakdowns would help reduce GHG emissions from these levels.

7.1.2.2 Other Gaseous Emissions

Common gaseous emissions other than concerned GHGs from a coal plant are SO_2, CO and NO_x. As majority of coal power plants are equipped with water-based flue gas arresting systems or scrubbers (Flue Gas Desulphurization System – FGDS), major portion of these gases mixed with water to form acidic effluents. A sample measurement and report done for LVPP shows higher concentration of SO_2 in the stacks of Units 1 and 2. This leads to an issue of poor reliability of FGDS installed at LVPP and extensive potentials in SO_2 emissions from power plant stacks.

Ambient air quality measurements at limited locations and times shows compliance with the local standards for SO_2, NO_2, CO and O_3 levels around LVPP. However, it is vital to develop and implement more comprehensive ambient air quality measuring campaign year-round to make conclusions on this aspect.

7.1.2.3 Resource Depletion

Depletion of Coal: Major resource depleted is coal which is used as the main source of energy used at LVPP. The power plant is designed to operate at around 38% efficiency level and currently operated at an efficiency level of about 37%. However higher efficiencies could have been expected with high efficiency designs if proper planning has been done.

Another significant aspect of efficient power plants, in addition to the design, is the proper installation, operation & maintenance. The frequent plant shutdowns observed in LVPP could be attributed to these aspects. Hence additional resource losses including coal and diesel are recorded. However, these are direct economic costs, which are already accounted for.

Depletion of coal is a global externality felt by all countries relying on fossil fuels for their energy needs. Thus, the economic cost of coal depletion is not included in this study.

Depletion of ground water: The ground water is being withdrawn at the rate of 2,100 m^3/day which is used for coal yard & ash yard operations. This is considered as a short term depletion since this water is usually evaporated and not available for the replenishment of the same resource. However, in the absence of an opportunity cost for ground water, as observed by the surveys conducted in the area, ground water depletion is not considered an externality cost of LVPP.

Depletion of marine resources: The power plant requires sea water withdrawal at a rate of 175,500 m^3/hr and chlorinating to prevent fouling. This may lead to destruction of marine life such as benthic organisms. Another significant environmental concern of LVPP is the death of small species including micronutrients, microorganisms, eggs and larvae of marine animals due to high rate of water withdrawal. In the absence of scientific studies conducted on this issue, quantification of the same is not undertaken as part of this study. However, it is essential to carry out proper studies to validate this concern and quantify the impacts.

Depletion of local biodiversity: Environmental Impact Assessment (EIA) of the second stage of LVPP (2012) indicates the importance of the coastal habitat for turtles and other marine organisms and reports that, out of a total of seven living species of turtles in the world, five are reported to nest along the beaches of Puttalam – Kalpitiya coastal belt and two of them are considered to be globally threatened. However, according to local villagers, turtles are not found in the surrounding areas of the power plant. Detailed studies on this are not available.

7.1.2.4 Thermal Emissions

Thermal losses are common to any thermal power plant, but higher power generation efficiencies will reduce the thermal loss fractions from the operation. Two major sources of thermal losses observed in LVPP are from condenser losses and stack losses. Out of these two sources condenser losses are significant than stack losses.

According to a similar case study [35], it has been established that useful power output is 38%, stack loss of 7% and condenser rejection loss of 48%. Part-load operation could further deteriorate the power generation efficiency and increase thermal losses of the same above sources.

Seawater is the main source of cooling at LVPP. According to the information gathered; about 16 cubic feet of seawater per second is required for the condenser. This stream of water flows through 16,000 condenser tubes. The temperature of seawater increases by about 5°C degrees. This heated water is finally released to the sea. It was reported that LVPP is maintaining a temperature gap of 4–5°C temperature difference between seawater intake and discharge. Despite the temperature difference not being substantial, due to the high effluent volumes and prevailing seawater movement patterns (water currents), this could lead to severe damages to local ocean biodiversity.

7.1.2.5 Heavy Metal Pollutants in Emissions

It has been proven that, coal contains Hg, As, Pb and Cr in micro concentrations. These metallic contaminants could be emitted mixed with solid emissions such as fly ash/bottom ash or more potently with gaseous emissions due to prevailing higher temperatures during the combustion process. Similar to the gaseous emissions mentioned earlier, metallic emissions too combine with scrubber unit medium; water and get discharged.

According to a sample analysis and report done for LVPP, the Pb level has been found to be below the permissible level. However, no results were observed on As and Hg in the same study due to an error in the measuring equipment.

7.1.2.6 Noise and Vibration

As common to other mechanical operations, LVPP too emits substantial levels of noises and creates vibrations along with its operation. According to the sample test report, it was observed that at the boundaries of LVPP, the noise and vibration levels are maintained at acceptable levels. However, during the site visit made by the study team, heavy noise levels were observed inside the plant and employees were provided with ear protective gear No internal noise level measurements or reports were available for review. Higher noise levels inside the plant environment could lead to wide range of health impacts on employees. During plant site visit, it was informed that all employees are subjected to regular health check-ups.

7.1.2.7 Particulate Emissions

Both PM_{10} and $PM_{2.5}$ emissions are common in coal power plants. As such, LVPP also emit above emissions, starting from the raw material stage up to stack emissions and post combustion ash storages.

According to the field sample measurements, total PM levels in the stack observed from LVPP are of a satisfactory level, except during breakdowns of emission control devices. For instance, during a sampling period, measuring team has observed part of the PM control device (Electro-static precipitator – ESP) was partially out of order and therefore, PM level of the plant (Unit 1) was high, despite still being below the maximum permissible limit. Since the power plant is in Kalpitiya peninsula where very high wind is prevalent, the particulate emission is creating substantial issues in the local area.

In addition to the stack emissions of PM, coal storage yard and ash piles too contribute to the particulate emissions. This situation is further aggravated during heavy monsoon windy periods. Preventive action has been taken in minimizing particulate emissions from these sources such as building a wind barrier wall/structure (wind fencing) and spraying of water continuously on the ash piles. During the study period, the extension of the wind barrier walls was in progress. A field sample measurement at selected locations during specific times shows a satisfactory result in PM_{10} and $PM_{2.5}$ emission levels in ambient air at LVPP. However, more comprehensive, year-round ambient air quality measurement campaign must be implemented to establish the effectiveness of the PM control measures. Further, it was observed that the environment inside the power plant is dusty and air quality measurements need to be taken within the power plant in addition to outside.

7.1.2.8 Water Pollution

A few major water pollution instances were explained above in relation to gaseous, thermal and heavy metal emissions. In addition, water pollution (sea pollution) due to coal particle emissions were observed during coal unloading and the transferring processes. It was observed that preventive/minimizing devices have been installed for coal transfer processes from barge to conveyor. It was also noted that the scrubber effluent is directly discharged to the sea.

7.1.2.9 Fugitive Emissions

Methane and Non-methane volatile organic compounds (NMVOCs) are potential fugitive emissions from coal power plants, especially from coal storages. Except for once, on-site measurements have not been conducted at LVPP to identify fugitive emissions.

7.1.3 GHG Related Global Externality Cost of Lak Vijaya Power Plant

7.1.3.1 Physical Quantification of the GHG Emissions

As mentioned in Section 7.1.2.1, coal power plants emit GHGs such as CO_2, CH_4 and N_2O due to combustion of coal and diesel. Table 7.1 provides GHG emissions from LVPP from 2011 to 2017 due to use of coal, whereas Table 7.2 provides GHG emissions due to the use of diesel during the same period. Total GHG emissions during this period is given in Table 7.3.

Table 7.1: GHG Emissions due to use of Coal in Lak Vijaya Power Plant, 2011-2017

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	1,038.1	1,403.7	1,469.4	3,524.1	4,457.8	5,066.9	5,120.6
Coal consumption (million kg)	395.2	624.9	677.6	1,363.6	1,880.0	2,004.0	2,086.5
CO_2 (million kg)	964.6	1,525.2	1,653.8	3,328.1	4,588.5	4,891.1	5,092.5
CH_4 (million kg)	0.01	0.02	0.02	0.04	0.05	0.05	0.05
N_2O (million kg)	0.02	0.02	0.03	0.05	0.07	0.08	0.08
GHG (million kg CO_2e)	970.12	1,534.0	1,663.4	3,347.3	4,615.0	4,919.3	5,121.9

Table 7.2: GHG Emissions due to use of Diesel in Lak Vijaya Power Plant

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	1,038.1	1,403.7	1,469.4	3,524.1	4,457.8	5,066.9	5,120.6
Diesel consumption (million kg)	3.96	1.872	1.593	8.343	2.709	5.211	3.717
CO_2 (million kg)	12.62	5.96	5.08	26.58	8.63	16.60	11.84
CH_4 (million kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O (million kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHG (million kg CO_2e)	12.66	5.99	5.09	26.68	8.66	16.66	11.89

Table 7.3: Total GHG Emissions from Lak Vijaya Power Plant

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	1,038.1	1,403.7	1,469.4	3,524.1	4,457.8	5,066.9	5,120.6
CO_2 (million kg)	977.17	1,531.15	1,658.88	3,354.69	4,597.11	4,907.73	5,104.32
CH_4 (million kg)	0.01	0.02	0.02	0.04	0.05	0.05	0.05
N_2O (million kg)	0.02	0.02	0.03	0.05	0.07	0.08	0.08
GHG (million kg CO_2e)	982.79	1,539.97	1,668.44	3,374.00	4,623.63	4,936.02	5,133.76

7.1.3.2 Calculation of GHG Emission Related Externality Cost of Lak Vijaya Power Plant

In the calculation of externalities of GHG emissions by LVPP, the benefit transfer approach described in Section 5.1 was used.

Externality Cost of CO_2 Emissions

Table 7.4 provides estimates for the LVPP based on the externality cost estimated per ton of CO_2 emissions.

Table 7.4: Externality Cost of CO_2 Emissions of Lak Vijaya Coal Power Plant

Year	Externality Cost of CO_2 Emissions ($US\$_{2007}$/ton)	Total Externality Cost	
		Nominal US$	Nominal Rs.
2011	32	33,847,202	3,757,039,510
2012	33	55,786,783	7,140,708,151
2013	34	63,517,743	8,193,788,913
2014	35	134,872,134	17,533,377,441
2015	36	193,904,898	26,371,066,088
2016	38	222,877,125	32,540,060,273
2017	39	242,663,476	36,399,521,328

Externality Cost of CH_4 and N_2O Emissions

Table 7.5 provides estimates for the externality costs of CH_4 and N_2O emissions by LVPP.

Table 7.5: Externally Cost of CH_4 and N_2O Emissions by Lak Vijaya Power Plant

Year	Externality Cost of CH_4 Emissions			Externality Cost of N_2O Emissions		
	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.
2011	910	10,546	1,170,621	12,000	199,987	22,198,548
2012	940	16,983	2,173,820	12,000	321,048	41,094,135
2013	970	19,322	2,492,482	13,000	384,511	49,601,954
2014	1,000	41,648	5,414,227	13,000	791,243	102,861,643
2015	1,000	57,239	7,784,514	13,000	1,109,253	150,858,447
2016	1,100	68,853	10,052,519	13,000	1,206,996	176,221,371
2017	1,100	72,825	10,923,775	14,000	1,379,668	206,950,145

Total Cost of GHG Related Global Externalities of Lak Vijaya Power Plant

Table 7.6 provides the final summary of externality cost of GHG emissions by LVPP.

Table 7.6: Total Externality Cost of GHG Emissions by Lak Vijaya Power Plant

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	34,057,735	3,780,408,680	1,038.10	3.28	3.64
2012	56,124,814	7,183,976,105	1,403.70	4.00	5.12
2013	63,921,576	8,245,883,349	1,469.40	4.35	5.61
2014	135,705,025	17,641,653,311	3,524.10	3.85	5.01
2015	195,071,390	26,529,709,049	4,457.80	4.38	5.95
2016	224,152,974	32,726,334,162	5,066.90	4.42	6.46
2017	244,115,969	36,617,395,248	5,120.60	4.77	7.15

7.1.4 Estimation of Other Externality Costs of Lak Vijaya Power Plant

The following pollution sufferers could be identified related to the pollutants indicated in the section 7.1.2. .

1. Nearby communities including school children (mainly 3 Grama Niladhari Divisions (GNDs) of Kalpitiya Divisional Secretariat Division (DSD) - severely affected.
2. Workers of the power plant (800).
3. Migrant agricultural labourers.
4. Workers in other establishments in the area.
5. Visitors/ Tourists.
6. Rest of the country.
7. Global community.
8. Non-human species (plants, animals, fish, and other organisms).

As highlighted in Section 2.3, the estimation of externality costs of LVPP[2] were carried out at both the global level and local level.

To capture as many externalities directly affecting the local communities as possible, multiple approaches were used as listed below:

Approach 1: Estimation of damage costs based on household surveys and key informant interviews conducted among nearby communities focusing on agricultural, health household mitigation measures and fishery impacts

Approach 2: Costs estimated using Benefit Transfer Approach for costs that are not covered by the household survey. (mainly the costs of air pollution incurred at the national level) and the costs of natural resources (especially water) and other costs of mitigation that are currently incurred at the plant premises .

Approach 3: Proposed mitigation costs + costing for remaining pollutants using Benefit Transfer Approach

[2]The overall assessment of externality costs of LVPP takes the viewpoint of the society and an economic analysis on the impacts are performed. Comparisons were made between with and without scenarios to the extent possible. Market values were converted to economic values to the extent possible. When market prices are not available, environmental valuation methods were used to derive the estimates for costs and benefits.

7.1.4.1 Approach 1: Estimation of Damage Costs based on Household Surveys and Key Informant Interviews

Data collection Methods

Two main primary data collection methods were employed, key informant interviews and household surveys. These data were supplemented by the secondary sources of data including published statistics and relevant academic literature.

1. **Key Informant Interviews**

Two main key informant interviews were carried out. The first one was conducted by the experts in the study team with farmers on 27.06.2019 at Narakkalliya GND and the second was conducted by the survey coordinator with fisherman, farmers, and other residents in three GNDs on 13-14 July 2019.

2. **Household Surveys**

Main household survey was conducted among the immediately affected community living in 3 Grama Niladhari Divisions (Narakkalliya GND, Paniadiya-Illanthadiya GND and Norochcholei GND) of the Kalpitiya DSD belonging to Puttalam District of the North-Western Province. A structured questionnaire was developed by the experts in the study team and various facets of impacts have been incorporated in the development of the questionnaire. Households were randomly selected with the assistance of the village community. Survey was carried out by undergraduate students of the University of Sri Jayewardenepura (guided by the experts in the study team and assisted by a survey coordinator) in the 3 GNDs between 13thand 14thJuly 2019. The survey resulted in usable responses from 184 households.

Sample

The following table provides total population and the details on gender distribution in the 3 GNDs.

Table 7.7: Total Population and Gender by Grama Niladhari Division

GN Division	Female	Male	Total population
Narakkalliya (620)	972	909	1,881
Paniyadiya (621)	1,696	1,422	3,118
Norochchola (621 A)	2,363	2,257	4,620
Total	**5,031**	**4,588**	**9,619**

Table 7.8 details on number of families and the sample selected from the 3 GNDs. The surveyed households are indicated in the map given in Figure 7.1.

Table 7.8: Population and Sample Selected from the 3 GNDs

GN Division	Number of Families	Sample selected
Narakkalliya (620)	418	58
Paniyadiya (621)	716	121
Norochcholai (621 A)	1,122	5
Total	**2,256**	**184**

Figure 7.1: Locations of Surveyed Households

The questionnaire

The questionnaire intended to collect following information from the households:

1. General information of the area, Socioeconomic data of the household including details of each and every family member, employment etc.
2. Disturbances experienced due to the LVPP in a Likert scale and the situation during the windy season whether there is any significant change the health problems and other issues.
3. Impact on agricultural crops: short term vegetable crops (with and without LVPP) and their cultivation details, dust mitigation measures and their costs, use of hired labourers and their health issues; perennial crops and the impacts
4. Impact on fisheries Details on fish catch (with and without LVPP) and the harvesting details, changes to the types of fish, abundance of fish, distances travelled
5. Health impacts: Children born with low birth weight, miscarriages, premature births, details on cancer patients, kidney patients (contingent valuation scenario to elicit willingness to pay towards avoidance of health impacts).
6. Preventive expenditure on mainly dust mitigatory measures

Results

Results of the questionnaire survey were utilized for different valuation methods that were used to evaluate agriculture, fishery, and health impacts as well as mitigatory actions. The focus of the results is to summarise the damage costs and other general details of the survey are not elaborated, therefore.

7.1.4.1.1 Impacts on agricultural activities and associated costs

These costs are mainly due to the coal dust that is blown with heavy winds from the coal yard.

Estimation Methodology – Effect on Production Method

This method is based on a linkage between a change in the state of the environment and ultimately a change in good or service that is traded in the market and therefore has an observable price. The physical linkage is typically described by a cause-effect relationship which links for example, the level of air pollution (cause) to a change in harvest rates (effect). The expected change in the quantity of crop harvested is then converted into monetary units using the prevailing market or economic prices. If the farmer intends to maintain the same harvest, he may have to incur additional costs to keep the air pollutants away.

There are four main types of economic impacts in the affected areas around the LVPP.

a) Reduced income due to changes of the seasonal crops grown.
b) Increased expenditure on water pumping (electricity cost) that is used to run sprinklers.
c) Reduced income due to the reduction of coconut yield of the existing coconut plants.
d) Reduced income due to the uprooting of the coconut trees due to the lowered yield.

(a) Reduced income due to changes of the seasonal crops grown

Coal dust has led to a shift from high valued crops (chillies and tobacco) to beet root and other crops. According to the farmers, tobacco and chillies are sensitive to dust and illustrates a significant reduction of yield when grown under the coal dust. Therefore, farmers have to opt for crops that could reasonably withstand coal dust and beet root was one such crop but with a lower value. According to the key informants, this shift has reduced the income per acre per year by Rs.12,637,500 and the total affected area is between 30-50 acres.

Table 7.9: Lost Income due to the Change of Crops

	Lower estimate	Upper estimate
Total affected acres	30	50
Loss per acre per yr	12,637,500	
Value Rs. per year	379,125,000	631,875,000

(b) Increased expenditure on water pumping (electricity cost) for sprinklers in vegetable farming areas

From the survey data, it has been found that farmers in the sample on average use sprinklers for 228.5 hrs when the coal dust is present. And when the dust is not there, on average the sprinkler usage is only for 131.8 hrs. Therefore, the total additional number of hrs of sprinkler use due to coal dust for the farmers in the sample is 96.7 hrs per month. The survey data indicates that the average cost per month is Rs. 9,692 and the total cost for the sample per year is Rs. 937,039 and extrapolated value for the population is Rs. 11,426,816 per year.

(c) Reduced income due to the reduction of coconut yield of the existing coconut plants

Coconut trees showed retarded growth and reduced yield due to the coal dust. There is a burnt appearance in the leaves and covered with black soot. It was observed that the yield reduction per coconut tree per harvest was about 20 nuts and there are 30 acres that are affected in the sample. Economic value of a coconut was considered as Rs. 108 (FOB value) taking into account the total export value generated from all coconut related products. The total annual economic cost is due to damaged coconut trees is estimated to be Rs. 86,400,000.

(d) Reduced income due to the uprooting of the coconut trees due to the lowered yield

It was observed that the villagers have uprooted some of the affected coconut trees in their lands. Total number uprooted in the sample area was recorded as 142 trees. When this value is extrapolated to the population, the loss to the economy is Rs. 56,409,809. However, some people mentioned that the uprooted trees could be several thousands.

7.1.4.1.2 Impacts on fisheries

These costs are due to multiple and combined impacts of the LVPP. Water withdrawal in large quantities from the ocean could affect the benthic communities and thereby the fishery yield. The power plant effluents with higher temperature affect the sensitive organisms and will have an impact on the food chains.

Estimation Methodology – Effect on Production Method

This method is based on a linkage between a change in the state of the environment and ultimately a change in good or service that is traded in the market and therefore has an observable price. The physical linkage is typically described by a cause-effect relationship which links for example, the level of water pollution (cause) to a change in harvest rates (effect). The expected change in the quantity of fish harvested is then converted into monetary units using the prevailing market or economic prices.

During the survey, the fishermen were questioned on the harvest some 8-10 years ago and the following table summarises the data and the final estimates.

Table 7.10: Estimation of the Value of Lost Fishery

	Without the LVPP (10 years ago)		**With the LVPP**	
	Lower estimate	Upper estimate	Lower estimate	Upper estimate
Fish harvest (kg per day)	100	200	10	15
Common types of fish	Etawalla, Balaya, Hurulla, lobster, crabs, Meewetiya		Etawalla, Balaya, Hurulla	
Value of lost fishery (Rs. per year)			**1,047,000,000**	**1,788,000,000**

Note: fishing days per year = 120; price range = Rs. 150-800 per kg; total number of fishermen = 250.

7.1.4.1.3 Impacts on Human health

Estimation methodology: Human Capital Approach /Cost of Illness Approach

Cost of Illness (COI) estimates externality costs due to changes in private and public expenditure on medical commodities and earnings lost due to days not worked resulting from the suffering from various impacts related to noxious facilities. There are two types of costs: direct costs and indirect costs. Direct costs measure the resources used to treat an illness while indirect costs measure lost productivity such as the effects of the illness on the ability of either patients or their care givers to work (e.g. lost income) or engage in other activities (e.g., cleaning the house).

The respondents were asked to rank the disturbances experienced due to the coal power plant and the following table elaborates the answers.

Table 7.11: Disturbances Ranked by the Respondents

		Fully Agreed (Rank 5)		Agreed (Rank 4)		Total	
		Nos.	%	Nos.	%	Nos.	%
1	You have been affected by coal power plant	106	58	42	23	148	80
2	There is a negetive impact from coal dust	89	48	47	26	136	74
3	There is a negetive impact from Fly ash	60	33	43	23	103	56
4	Dust from the coal plant has affected your health	59	32	55	30	114	62
5	Disturbances due to dust inside the house	62	34	54	29	116	63
6	Negative impacts on agricultural crops	66	36	51	28	117	64
7	Reduction of fish catch after the coal power plant	28	15	6	3	34	18
8	Risk of having Cold/ Cough/TB/ Asthma	56	30	50	27	106	58
9	Reduced ability to work	63	34	52	28	115	63
10	Breathing difficulties	65	35	49	27	114	62

Among the respondents, 80% have agreed that they have been affected by the LVPP and 65% have indicated breathing difficulties and 58% have indicated that they have a risk of having other respiratory illnesses. In addition, this information was confirmed in other sections of the questionnaire. Many have indicated their condition is getting worsened during the windy season. Based on this data, the following estimation was performed to derive a value for health damages.

Table 7.12: Estimation of Cost of Illnesses

	Number of people affected	**Cost of illness per year 2018 values** [36]	**Total value for the sample**	**Value for the population**
Asthma, cough and breathing issues	56	30,017.53	1,490,216	18,271,344
Skin rashes	7	15,265.39	106,857.7	1,310,168
Total				**19,581,512**

In addition, there are temporary agricultural workers who are working in the agricultural fields.

Table 7.13: Cost of Illnesses to Temporary Agricultural Workers

	Number of people affected	**Cost of illness per year**	**Total value for the sample**	**Value for the population**
Eye irritations	4	30,018	120,070	1,472,164
Skin irritations	8	15,265	122,123	1,497,335
Breathing difficulties	6	30,018	180,105	2,208,246
Total				**5,177,745**

It must be noted however, that the above numbers of affected people are probably vastly underestimated. Probability of identifying a health problem and taking treatment is rather low among the people with lower education and income levels.

Table 7.14 provides a summary of other heath related data collected from the sample of 184 households.

Table 7.14: Summary of the Heath Related Data Collected from the Sample

Health issue	Number
Child births during the last 7-8 years	102
Premature births	7
Children born with low birth weight	14
Number of miscarriages	11
Family members suffering from kidney failures	9
Family members suffering from cancer	6

Some of the reasons given by the doctors (as indicated by the respondents) for the miscarriages include the following:

- Brain was not developed
- cancer on eyes/fit
- a liquid around lungs of the baby
- problem with lungs

The types of cancer are as follows:

- Brain - 1
- Throat – 1
- Oral cancer - 4

Incidence rate of oral cancer in Sri Lanka for year 2011 is 14.7 per 100,000 population which gives an annual value of 0.122 for 828 (185 x 4.5) people. If the cancer incidence is within the last 10 years, this gives a value of 1.22 for 828 people. Since 4 is higher than 1.22, there is above average rate of cancer incidence in the area[3]. More data are required to decide on inclusion of these data into the cost calculations. Potential mortalities can be valued using VSL (Value of Statistical Life). Other health issues indicated by the people included skin rashes, asthma, blisters, itching, breathing problems, cough etc.

Alternative estimation methodology: Contingent Valuation Method (CVM) to value health impacts

This is a survey based method that explicitly asks individuals to place values upon environmental assets. The method is legally accepted in USA and in Sri Lanka for damage estimation and for claiming purposes. Guidelines are available from USA, NOAA (National Atmosphere and Oceanic Administration). The method involves presenting a hypothetical scenario to respondents to value the health damages using a survey instrument.

This resulted in a mean value of Rs. 2,621.15 per household (one time) and the per yr per household value is Rs. 262.12. Value for the total population is Rs. 591,332 per year. It seems that this value is largely an underestimation indicating the lower health consciousness among the community.

Estimation of Costs of Mitigative Measures by the Households

Estimation Methodology: Averting Behaviour Method/Preventive/Mitigative Expenditure Method

The preventive expenditure method is a cost-based valuation method that uses data on actual expenditures made to alleviate all environmental impacts. In case of power plants, the averting or mitigating behaviour method infers a monetary value for some environmental externalities by

[3] In another survey carried out recently ((17-18 August 2019) in the same area (Kudawa village), 3 cancer patients were found among a sample of 70 people and 4 kidney patients were found among 170 people.

observing the costs people are prepared to incur in order to avoid any negative effects from those externalities.

These methods assess the value of non-marketed commodities such as cleaner air and water, through the amount individuals are willing to pay for market goods and services to mitigate an environmental externality, or to prevent a utility loss from environmental degradation, or to change their behaviour to acquire greater environmental quality.

This method can be used to estimate damages due to fugitive emissions from fuel storage such as coal yards and fly ash disposal mechanisms, costs of contaminating ground water, sea water and soil through the toxic materials, contained in ash and other discharges. It was found that the people in the area spend time, money and resources for additional cleaning as a mitigatory measure against the coal dust. This is an economic cost since it involves opportunity cost. In addition, they have carried out alternations to their houses in order to avoid coal dust.

(a) Time cost on cleaning
Additional hrs spent on average on such cleaning activities in a week is 1.6 hrs and cleaning is done on average during 4 days a week. Taking a value of labour as Rs. 1,000, this involves a value of Rs. 332,800per year for the sample and a value of Rs. 4,080,417 for the population.

(b) Material cost on cleaning
Total additional cleaning material cost per month is Rs.31,200 and per year value is Rs.374,400 which gives total cleaning cost for the sample as 707,200 and total cost for the population (total households 2,256) is Rs. 8,670, 887.

(c) Cost of house alterations to avoid pollution
Average Cost of house alterations per household is 114,188 and total for the population is 1,400,038. Assuming that the alteration will last for 10 years, the annual value is taken as Rs. 140,004.

Table 7.15: Summary Cost Estimates

Cost item	Value Rs. per year (lower estimate)	Value Rs. per year (upper estimate)
Costs on agriculture		
Lost income due to the change of crops	379,125,000	631,875,000
Increased expenditure on water pumping	11,426,816	11,426,816
Reduced income due to the reduction of coconut yield	86,400,000	86,400,000
Reduced income due to the uprooting of the coconut trees	56,409,809	56,409,809
Value of the lost fishery	1,047,000,000	1,788,000,000
Health costs		
costs of illnesses for resident villagers	19,581,512	19,581,512
Cost of illness for temporary agricultural workers	5,177,745	5,177,745
Costs of Mitigative Measures		
Time cost on cleaning	4,080,417	4,080,417
Material cost on cleaning	8,670, 887	8,670, 887
Cost of house alterations	140,004	140,004
Total	**1,609,341,303**	**2,603,091,303**

Table 7.16: Externality Cost of LVPP - Agriculture, Health and Fishery Impacts

Social damage	Lower estimate	Upper estimate	Unit
Annual cost (for 5120.6 GWhrs)	1,609,341,303	2,603,091,303	Rs.
Annual cost	9,196,236.02	14,874,807.45	US$
Cost per 1 kWh	0.1796	0.2905	**US Cents**
Cost per 1 kWh	0.3143	0.5084	Rs

7.1.4.2 Approach 2 - Costs estimated using Benefit Transfer Approach for costs that are not covered by the Household Survey

This approach considers estimation of damage costs due to air pollutants from stack emissions and other costs incurred by the operation of the plant.

1. Costs of air pollutants

Muller and Mendelsohn [37] models the marginal damage costs of pollutants, The model begins by computing total damages from the baseline level of emissions of six different pollutants: coarse particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), NOx, SO_2, volatile organic compounds (VOC), and ammonia (NH_3). One ton of a specific pollutant is then added to the baseline emissions from a particular source. Total damages are recomputed. The resulting change in total damages is the marginal damage due to adding one ton of the specific pollutant at that particular source. Note that this methodology captures the damages from secondary pollution formation through atmospheric chemistry, and properly attributes the change in damages back to the source of emission. This experiment is repeated 60,000 times: covering the nearly 10,000 point and aggregated nonpoint sources in the contiguous United States and for the six pollutants listed above. The marginal damages of emissions by quantile and Median Marginal Damage Cost (MDC) values are given in Table 7.17.

Table 7.17: Marginal Damages of Emissions by Quantile (US$/ton/year)

Pollutant	1st percent	25th percent	50th percent	75th percent	99th percent	99.9th percent	*Expected Marginal Damage*
$PM_{2.5}$	250	700	1,170	1,970	12,400	41,770	3,220
PM_{10}	60	120	170	280	1,960	6,550	450
NO*x*	20	180	250	370	1,100	1,780	260
NH_3	100	300	900	2,000	20,620	59,450	2,520
VOC	40	120	180	280	1,370	4,540	730
SO_2	220	550	970	1,300	4,130	10,860	1,310

Table 7.18: Median Marginal Damage Cost of Pollutants

Pollutant	Median Marginal Damage Cost (US$/ton/year)	Marginal Damage Cost (US$/ton/year) lowest values
$PM_{2.5}$	3,220	250
PM_{10}	450	60
NOx	260	20
NH3	2,520	100
VOC	730	40
SO_2	1,310	220

Table 7.19 illustrates cost of air pollutants calculated based on the lowest values and the median marginal from the above table adjusted for GDP PPP and applied to the total pollutant quantities calculated for the LVPP.

Table 7.19: Cost of Air Pollutants

Pollutant	Total Generation (t/yr)	Total Cost based on 1st percent marginal damage cost (Rs. per year)	Total Cost based on expected marginal damage cost (Rs. per year)
SO_2	16,819	129,506,300	771,151,150
NO_X	6,240	4,368,000	56,784,300
PM	116,052	1,015,455,000	13,079,060,400
Total		**1,149,329,300**	**13,906,995,850**

Notes: Exchange rate 1 US$ = Rs.175; PM is assumed to be $PM_{2.5}$

The above estimate of 771 million damage cost based on expected marginal damage cost of SO_2 is in direct comparison with the estimate derived from European Union. Ecofys (2014) calculates cost of terrestrial acidification as € 0.2 (per kg SO_2 eq). The total SO_2 emission from the LVPP is 16,819 tons per year which results in cost from acidification equal to Rs. 710,546,106 (in 2019 prices).

This comparison provides a justification for use of expected marginal damage cost over the 1st percent marginal damage cost. Therefore in the subsequent calculations, total cost of Rs billion 13.9 will be used.

2. Cost of water used in the plant premises to mitigate coal and ash dust

PUCSL (2019) reports the total water requirement of coal yard and ash yard for wind season. The cost of this water can be calculated at a rate of Rs. 5 per m^3. Table 7.20 provides the details.

Table 7.20: Cost of Water Required for Coal and Ash Yards

Purpose	Quantity of water (m^3/day)	Annual Cost (Rs.)
Coal yard		
Coal yard mist blowers attached to stacker and reclaimer	9	
Mist blowers attached to bowser	22	
Water spray gun attached to conveyer belt both sides	1680	
Sub Total	1711	1,561,288
Ash yard		
Water bowsers (water used in IWW plant)	162	
Hand spraying (using shallow wells	234	
Sub Total	396	361,350
Total	**2,107**	**1,922,638**

Notes: wind season assumed to be 6 months

3. Costs of other mitigation measures incurred at the plant premises

The LVPP has undertaken several mitigation measures in order to reduce pollution due to coal and ash dust. The following table provides details of modification works done and their costs and the equivalent annual cost.

Table 7.21: Cost of Modification Works

Mitigation measure	Cost (Rs. million)	Equivalent Annual Cost (Rs. million)[1]
Wind barrier	751	122.22
Mist Cannon spray	200.1	32.57
Mist Blowers	6.0	0.98
Sprinklers	58.2	9.47
Sub Total	**1,015.3**	**165.24**

Notes: 1.discount rate = 10%; operational life = 10 yrs.
Source: PUCSL (2019)

It must be noted however, despite these mitigation measures, nearby communities have experienced the damages continuously. Some of the rectification works done for the LVPP are given in Table 7.22.

Table 7.22: Costs of Rectification Works

Mitigation measure	Cost (Rs. million)	Equivalent Annual Cost (Rs. million)[1]
Wastewater Treatment plant	23	3.74
Sewerage Treatment plant	1.5	0.24
Coal & Cinder water basin	80	13.02
CEMS	54.4	8.85
Sub Total	**158.9**	**25.86**

Notes: 1. discount rate = 10% and operational life = 10 yrs.

Costs of the routine works are given in Table 7.23. This mainly involves mitigation measures for coal and ash yards.

Table 7.23: Costs of Routine Operations

Item	Annual Cost (Rs. million)
Mitigation measures for Coal Yard	19.7
Mitigation measures for Ash Yard	19.2
Sub Total	**38.9**

Costs related to new Installation of equipment for pollution control & purchasing for monitoring works are given in Table 7.24.

Table 7.24: Costs of New Installations for Pollution Control

Mitigation measure	Cost (Rs. million)	Equivalent Annual Cost (Rs. million)[1]
Multi Parameter for water Quality	0.4	0.07
Portable Dust Device	0.6	0.10
Permanent Ambient Air Quality		0.00
Monitoring Station	158	25.71
Sound meter	0.65	0.11
Portable Flue Gas Analyzer	2	0.33
Free Chlorine Portable meter	0.1	0.02
Sub Total	**161.75**	**26.32**

Notes: 1.discount rate = 10%; operational life = 10 yrs.

Table 7.25 provides the summary of mitigation measures.

Table 7.25: Summary of the Costs of Mitigation Measures

Mitigation measure	Annual cost (Rs. million)
Costs of modification works	165.24
Costs of rectification works	25.86
Mitigation measures for coal and ash yard	38.91
Costs of new installations for pollution control	26.32
Total	**256.33**

Table 7.26 summarises the costs calculated under Approach 2.

Table 7.26: Summary of the Externality Costs Estimated using Approach 2

Item	**Annual Cost (Rs.)**	
Costs of air pollutants estimated using Benefit Transfer Approach	13,906,995,550	
Cost of water used in the plant premises to mitigate coal and ash dust	1,922,638	
Cost of other mitigation measures	256,330,000	
Total	14,165,248,188	

Approach 2 gives a total externality cost of Rs. 14.16 billion.

Table 7.27: Summary of Total Costs Calculated using Approach 1 and 2

Item	**Total Damage Cost (Rs. per year) (Lower Bound)**	**Total Damage Cost (Rs. per year) (Upper Bound)**
Damage cost estimated based on household surveys and key informant interviews conducted among nearby communities focusing on agricultural, health household mitigation measures and fishery impacts	1,609,341,303	2,603,091,303
Costs of air pollutants estimated using benefit transfer approach		13,906,995,55
Costs of water used and costs of other mitigation measures incurred at the plant		258,252,638
Total	**15,774,589,491**	**16,768,339,491**

Table 7.28 provides final external costs in relation to power generated. It includes costs calculated using approach 1 and 2 and the GHG costs calculated in section 7.1.3.2.

Table 7.28: Total Externality Costs of LVPP

Parameter	**Lower Bound Estimate**	**Upper Bound Estimate**
External Costs calculated using Approach 1 and 2		
External cost in Rs.	15,774,589,4913,016,923,241	16,768,339,491
External cost in US$	90,140,511	95,819,083
External cost in US$ per kWh(considering the annual generation of 5120.60 GWh)	0.0176	0.01871
External cost in US$ cents per kWh	3.080	3.275
External Costs due to emission of GHGs[1]		
External cost in US$ cents per kWh	4.77	4.77
External cost in Rs. per kWh	4.77	4.77
External cost in Rs. per kWh	7.15	7.15
Final Total Cost		

Total external cost of LVPP in US$ cents per kWh	6.53	6.641
Total external cost of LVPP in Rs per kWh	10.231	10.425

[1]Estimated for the year 2017

Omissions from the Above Study

List of items that are not valued:

1. Health damage costs of the workers of LVPP- Loss of productivity (leave from work).
2. Costs related to water withdrawals for the mist cannon spray, mist blowers, sprinklers Pumping costs, Labour costs and opportunity costs.
3. Impacts on biodiversity:
    - Impacts on benthic communities, sea living organisms and the related dependent species,
    - Impacts on other natural vegetation.
4. Impacts on school children - lowered attendance.
5. Cost of coal dropped into the sea and deposited near the jetty and the seabed when coal transported from ships is loaded to the barges.
6. Cost of coastal erosion.
7. Costs of untreated water from the LVPP.

Table 7.29 provides details of wastewater discharges by LVPP, which have not been included in damage cost valuation.

Table 7.29: Wastewater Discharged by LVPP

Source of Wastewater	Quantity Generated (m3/day)	Treatment Process
Spills from Jetty	70 (assuming a maximum 100 mm rainfall per day over 700 m2	No treatment
Demineralization plant effluents	10,080 (Reject water of 420 m3 per hour out of 500 m3 of feedwater)	No treatment Discharged to sea with cooling water
Contaminated storm water	8,000 (assuming a maximum 100 mm rainfall per day over20 acres)	No treatment

Source: PUCSL (2017)

8. The costs related to cooling water withdrawn from the sea: Cooling water is taken from a near-shore intake point about 300 m away from the coastline. After being filtered through a trash rack and traveling screen the sea water is pumped by separate cooling water pumps. The amount of water pumped is 58,500 m3/hr per intake. There are three such intakes, which are approximately 32 m apart.
9. Possible negative impacts on the receiving area of the effluent in terms of loss of flora and fauna, habitat destruction, loss of spawning grounds, and any other adverse impacts.

7.2 Case Study on Yugadhanavi Power Plant in Kerawalapitiya

The Yugadhanavi Power Station is a Heavy Fuel Oil (HFO) fired combined cycle thermal power plant located in Kerawalapitiya, in the Western Province of Sri Lanka. Built on a 25-acre (0.10 km2) land, the power plant has a gross generation capacity of 300 MW, comprising two 100 MW GE Frame 9E Gas Turbines and one GE steam turbine (with Heat Recovery Steam Generator / Boiler). The power plant can produce up to 1,800 GWh of electricity annually.

Construction of the power station began in November 2007, and the Phase-1 of the power plant, capable of producing 200 MW using the two gas turbines, was commissioned in 2008. The steam turbine was installed and commissioned in February 2010, increasing the total generation capacity to its present value of 300 MW.

The power plant is located close to both the sea and the Muthurajawela tank farm (CPSTL). The proximity to sea allows the power plant to use sea water for cooling and 25,000 m^3 of sea water is circulated across the power plant cooling cycle every hour. But currently they recycle cooling water through a cooling tower and only the make-up quantity is demand from the sea.

The power plant is designed to run on 180cst Low Sulphur Fuel Oil (LSFO), making it one of the most efficient and economical power plants in the national grid. Whilst being able to run on lighter fuels such as natural gas and diesel, the ability of Yugadhanavi power plant to run on heavy fuels makes it unique in the Sri Lankan power system. However, the quality of fuel required for the power plant is not available with the Ceylon Petroleum Corporation (CPC) refinery, thus this fuel is imported to Sri Lanka as a finished product, exclusively for the use of Yugadhanavi power plant.

During the visit to the power plant, the following observations were made:

- Power plant maintains a pleasant green surrounding within the plant site,
- A dedicated environmental officer in position managing all necessary environmental initiatives,
- Plant operation is certified with ISO 14001 – Environmental management system,
- It was informed the plant is provided with a valid EPL issued by central environmental authority,
- Sea water used as a source of boiler makeup (subsequent to a complete desalination,and demineralization process) and cooling water directly, but hot water generated from the cooling process is recycled instead of direct discharge to the sea.

7.2.1 GHG Related Global Externality Cost of Yugadhanavi Power Plant

7.2.1.1 Physical Quantification of GHG Emissions

The power plant emits GHGs due to Heavy Fuel Oil (HFO) combustion. GHGs include CO_2, CH_4 and N_2O. Table 7.30 provides emissions from the power plant from 2011 to 2017.

Table 7.30: GHG Emissions due to use of HFO in Yugadhanavi Power Plant

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	1,186	1,465.0	460.2	657.6	671.4	891.8	1,186
HFO consumption (million kg)	228.90	303.28	86.22	129.70	137.02	188.55	228.90
CO_2 (million kg)	715.75	948.35	269.61	405.56	428.47	589.59	754.50
CH_4 (million kg)	0.03	0.04	0.01	0.02	0.02	0.02	0.03
N_2O (million kg)	0.01	0.01	0.00	0.00	0.00	0.00	0.01
GHG (million kg CO_2e)	718.28	951.70	270.56	406.99	429.98	591.67	757.17

7.2.1.2 Calculation of GHG Emission Related Externality Cost of Yugadhanavi Power Plant

In calculating the global externality cost of GHG emissions by Yugadhanavi Power Plant, the methodology described in Section 5.1 was adopted.

Externality Cost of CO_2 Emissions by Yugadhanavi Power Plant

Table 7.31 provides the damage cost of emitted CO_2 from Yugadhanavi (Kerawalapitiya) power plant during 2011-2017 period.

Table 7.31: Externality Cost of CO_2 Emissions by Yugadhanavi Power Plant

Year	Externality Cost of CO_2 Emissions (US$$_{2007}$/ton)	Total Externality Cost	
		Nominal US$	Nominal Rs.
2011	32	24,792,087	2,751,921,679
2012	33	34,552,841	4,422,763,663
2013	34	10,323,104	1,331,680,438
2014	35	16,305,277	2,119,686,035
2015	36	18,072,824	2,457,904,024
2016	38	26,775,279	3,909,190,789
2017	39	35,869,719	5,380,457,839

Externality Cost of CH_4 and N_2O Emissions by Yugadhanavi Power Plant

Table 7.32 provides the externality cost of methane (CH_4) and nitrous oxide (N_2O) from Yugadhanavi Power Plant. Table 7.33 provides the final summary of externality cost of GHG emissions.

Table 7.32: Externality Cost of CH_4 and N_2O Emissions by Yugadhanavi Power Plant

Year	Externality Cost of CH_4 Emissions			Externality Cost of N_2O Emissions		
	(US$$_{2007}$/ton)	Nominal US$	Nominal Rs.	(US$$_{2007}$/ton)	Nominal US$	Nominal Rs.
2011	910	27,327	3,033,306	12,000	72,070	7,999,825
2012	940	38,148	4,882,970	12,000	97,401	12,467,316
2013	970	11,415	1,472,507	13,000	30,598	3,947,120
2014	1,000	18,057	2,347,454	13,000	46,948	6,103,231
2015	1,000	19,458	2,646,254	13,000	50,591	6,880,387
2016	1,100	30,041	4,385,992	13,000	71,008	10,367,113
2017	1,100	39,214	5,882,075	14,000	99,816	14,972,421

Table 7.33: Total Externality Cost of GHG Emissions by Yugadhanavi Power Plant

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	22,995,884	2,552,543,064	1,186.0	2.10	2.33
2012	31,418,344	4,021,547,976	1,465.0	2.37	3.03
2013	9,203,927	1,187,306,541	460.2	2.25	2.91
2014	14,251,316	1,852,671,041	657.6	2.49	3.24
2015	15,484,767	2,105,928,418	671.4	2.70	3.68
2016	22,488,909	3,283,380,720	891.8	3.01	4.40
2017	29,539,716	4,430,957,389	1,193.6	3.02	4.53

7.3 Case Study on Kelanitissa Power Station in Peliyagoda

The Kelanitissa Power Station was first commissioned in 1964 with two steam turbine generator units of 25 MW each. Six Frame-7 gas turbines, each with 20 MW generating capacity, were added to the power station in the early 1980s. In 1997, a Frame-9 gas turbine of 115 MW, commonly known as the "FIAT" gas turbine was added to the power station. This increased the total capacity of the power station to 285 MW, located with the same premises. Due to increasing maintenance requirements and inefficiencies, the two steam turbines were decommissioned in 2005. One of the frame 7 gas turbines was also taken out of operation in 2005 and another in 2014, reducing the total generating capacity of the complex to its present capacity of 195 MW.

The gas turbine units of Kelanitissa Power Station comprise three assemblies; compressor, combustion chamber and turbine unit. The Brayton cycle, an open thermodynamic cycle, applies on the three airflow stages of compression, combustion, and expansion. Filtered air is taken from air inlet and directed to compressor. Inlet guide veins (IGV) are used to control the air flow.

Compressor assembly consists of several stages of rotating and stationary blades, which is designed to increase the pressure of the airflow. Compressed air is taken from different compressor stages for different purposes. Atomizing air is prepared further compressing this air through a pressure pump. This atomizing air and fuel supply directed to flame tubes in the side combustion chambers. Number of cylindrical type chambers can be seen depending on the type of gas turbine. Two spark plugs are used to provide initial ignition, and it spread to all others since they all are interconnected. Except atomizing air, compressed air flow from compressor passes through nozzle and enters the flame tubes from outside. This secondary air flow reduces the temperature of pressurized air to a level which can be passed through turbine unit depending on the safety limits of turbine material. Simultaneously, this air flow cools down the flame tubes. At the final stage, this high pressurized gas flowing through turbine assembly, rotating the whole machine. The compressor and turbine are fitted to same shaft.

Since gas turbines rotate at high speeds (5100 rpm for frame 7 GT), generator is connected through a gearbox, which reduces the speed to 3,000 rpm. A cranking motor is available to rotate the shaft at a slow speed when GT is not working to prevent the shaft from sagging, which could lead to shaft damage.

Main auxiliary systems of the gas turbine machines are the fuel oil system, the bearing and lubrication oil system and the cooling water system. Prior to entering the engine, fuel is processed in several stages. Diesel stored in tanks, firstly going through Fuel Oil Treatment Plant (FOTP). Inside the FOTP, using centrifugal pumps, dirt and other particles are separated and filtered. After purification, oil is stored in a separate tank. Oil supply for GTs are taken from a duct and pressurized by fuel pumps. This is required to maintain the ambient oil pressure for atomization process in the combustion chamber.

7.3.1 GHG Related Global Externality Cost of Kelanitissa Power Station

7.3.1.1 Physical Quantification of GHG Emissions

The power plant emits GHGs due to diesel combustion. GHGs include CO_2, CH_4 and N_2O. The following table provides GHG emissions by the power plant from 2011 to 2017.

Table 7.34: GHG Emissions due to use of Diesel in Kelanitissa Power Station

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	320.3	218.2	17.6	241.9	25.1	308.5	401.0
Diesel consumption (million kg)	356.45	250.92	18.64	251.78	26.38	321.47	422.98
CO_2 (million kg)	0.01	0.01	0.00	0.01	0.00	0.01	0.02
CH_4 (million kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O (million kg)	357.76	251.85	18.71	252.71	26.48	322.65	424.54
GHG (million kg CO_2e)	356.45	250.92	18.64	251.78	26.38	321.47	422.98

7.3.1.2 Calculation of GHG Emission Related Externality Cost of Kelanitissa Power Station

In calculating the global externality cost of GHG emissions by Kelanitissa Power Station, the methodology described in Section 5.1 was adopted.

Externality Cost of CO_2 Emissions by Kelanitissa Power Station

Table 7.35 provides the externality cost of CO_2 emissions by the Kelanitissa Power during 2011-2017 period.

Table 7.35: Externality Cost of CO_2 Emissions by Kelanitissa Power Station

Year	Externality Cost of CO_2 Emissions ($US\$_{2007}$/ton)	Total Externality Cost	
		Nominal US$	Nominal Rs.
2011	32	12,346,702	1,370,483,923
2012	33	9,142,227	1,170,205,095
2013	34	713,711	92,068,728
2014	35	10,122,620	1,315,940,621
2015	36	1,112,809	151,342,061
2016	38	14,598,893	2,131,438,450
2017	39	20,108,864	3,016,329,522

Externality Cost of CH_4 and N_2O Emissions by Kelanitissa Power Station

Table 7.36 provides the externality cost of methane (CH_4) and nitrous oxide (N_2O) emitted by Kelanitissa Power Station during 2011-2017.

Table 7.36: Externality Cost of CH_4 and N_2O Emissions by Kelanitissa Power Station

Year	Externality Cost of CH_4 Emissions			Externality Cost of N_2O Emissions		
	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.
2011	910	14,214	1,577,809	12,000	37,490	4,161,394
2012	940	10,543	1,349,487	12,000	26,919	3,445,580
2013	970	824	106,341	13,000	2,210	285,029
2014	1,000	11,710	1,522,261	13,000	30,444	3,957,670
2015	1,000	1,251	170,181	13,000	3,254	442,503
2016	1,100	17,109	2,497,906	13,000	40,440	5,904,173
2017	1,100	22,962	3,444,330	14,000	58,450	8,767,434

Table 7.37 provides the final summary of global externality cost of GHG emissions.

Table 7.37: Total Externality Cost of GHG Emissions by Kelanitissa Power Station

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	11,431,576	1,267,607,639	320.3	3.87	4.30
2012	8,301,946	1,061,137,514	218.2	4.21	5.38
2013	647,487	81,850,795	17.6	4.07	5.25
2014	8,835,544	1,146,957,156	241.9	4.20	5.46
2015	963,840	129,317,074	25.1	4.45	6.05
2016	12,243,017	1,785,616,313	308.5	4.75	6.94
2017	16,529,109	2,477,314,284	401	5.03	7.55

7.4 Case Study on Sapugaskanda Power Station

Sapugaskanda Power Station, located in Sapugaskanda in Western Province, is near the Sapugaskanda Oil Refinery of Ceylon Petroleum Corporation. It is the largest Diesel Power Station operated and maintained by Ceylon Electricity Board. The Power station was developed in 2 stages, where four of 20 MW SEMT Pielstick Engines were installed in 1986 followed by 8 of 10 MW MAN Engines were installed at the same premises in 1998. The two stages are identified as Sapugaskanda-A and Sapugaskanda-B.

The use of Sapugaskanda Power Station has reduced of late due to availability of LVPP, which generates electricity at a much lower cost. In addition, the old Pielstick engines have undergone several overhauls and have reached the end of their useful life. The newer MAN engines have also clocked more than 100,000 hrs., indicating the power station to have spent most of its useful life.

7.4.1 GHG Related Global Externality Cost of Sapugaskanda Power Station

7.4.1.1 Physical Quantification of GHG Emissions by Sapugaskanda Power Station

Sapugaskanda Power Station emits GHGs due to diesel combustion. Table 7.38 provides emissions from the power station from 2011 to 2017.

Table 7.38: GHG Emissions due to use of HFO in Sapugaskanda PowerStation

Year	2011	2012	2013	2014	2015	2016	2017
Generation (GWh)	1,186.0	1,465.0	460.2	657.6	671.4	891.8	1,186.0
HFO consumption (million kg)	228.89	303.28	86.22	129.70	137.02	188.55	228.90
CO_2 (million kg)	584	592	366	422	192	506	450
CH_4 (million kg)	0.02	0.02	0.01	0.02	0.01	0.02	0.02
N_2O (million kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHG (million kg CO_2e)	585.72	594.64	367.84	423.39	192.84	507.43	451.31

7.4.1.2 Calculation of GHG Emission Related Externality Cost of Sapugaskanda Power Station

In calculating the global externality cost of GHG emissions by Sapugaskanda PowerStation, the methodology described in Section 5.1 was adopted.

Externality Cost of CO_2 Emissions by Sapugaskanda Power Station

Table 7.39 provides the externality cost of CO_2 emissions by Sapugaskanda Power Station during 2011-2017.

Table 7.39: Externality Cost of CO_2 Emissions by Sapugaskanda Power Station

Year	Externality Cost of CO_2 Emissions ($US\$_{2007}$/ton)	Total Externality Cost	
		Nominal US$	Nominal Rs.
2011	32	20,213,627	2,243,712,650
2012	33	21,586,106	2,763,021,510
2013	34	14,032,659	1,810,213,084
2014	35	16,959,424	2,204,725,096
2015	36	8,104,157	1,102,165,358
2016	38	22,959,722	3,352,119,364
2017	39	21,376,744	3,206,511,667

Externality Cost of GHG Emissions by Sapugaskanda Power Station

Table 7.40 provides the externality cost of methane (CH_4) and nitrous oxide (N_2O) from Sapugaskanda Power Station.

Table 7.40: Externality Cost of CH_4 and N_2O Emissions by Sapugaskanda Power Station

Year	Externality Cost of CH_4 Emissions			Externality Cost of N_2O Emissions		
	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.	($US\$_{2007}$/ton)	Nominal US$	Nominal Rs.
2011	910	23,272	2,583,224	12,000	61,377	6,812,864
2012	940	24,894	3,186,395	12,000	63,559	8,135,503
2013	970	16,208	2,090,797	13,000	43,445	5,604,417
2014	1,000	19,617	2,550,243	13,000	51,006	6,630,811
2015	1,000	9,114	1,239,550	13,000	23,697	3,222,766

2016	1,100	25,694	3,751,396	13,000	63,600	9,285,664
2017	1,100	27,485	4,122,700	14,000	62,136	9,320,370

Table 7.41 provides the final summary of global externality cost of Sapugaskanda Power Station due to GHG emissions.

Table 7.41: Total Externality Cost of GHG Emissions by Sapugaskanda Power Station

Year	Total Externality Cost		Generation (GWh)	Specific Externality Cost	
	US$	Rs.		(USCts/kWh)	(Rs./kWh)
2011	18,752,470	2,081,524,199	910.9	2.23	2.47
2012	19,631,315	2,512,808,270	925.8	2.34	3.00
2013	12,513,570	1,614,250,516	572.9	2.46	3.17
2014	14,825,681	1,927,338,514	656.3	2.59	3.37
2015	6,944,824	944,495,976	294.4	2.76	3.76
2016	19,286,386	2,815,059,908	784.8	2.94	4.29
2017	17,609,896	2,640,988,255	692.7	3.10	4.65

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Annex 1: Legal Cases Against Poor Environmental Performance of LVPP

A court case has been filed by Sri Lanka Environmental Foundation in relation to environmental pollution by LVPP (Case Number - SC (FR) 282/16).Case briefing given as below; Source (https://efl.lk/portfolio/norochcholai-coal-power-plant/)

Extract//
The Lak Vijaya Coal Power Plant, more commonly known as the Norochcholai Coal Power Plant (NCPP) is located in the village of Narakkalli and Penaiyadi near Norochcholai, within Puttalam District, on the West Coast of the Kalpitiya Peninsula. The power plant was proposed by the Ceylon Electricity Board (CEB) in 1995 and the construction of the facility began in 2007. It was constructed in 3 phases and completed by September 2014, with a total power generation of 900 MW. The following is a tabulated description of EFL's engagement in mitigating the negative environmental and social impacts of the coal power plant.

Environmental Foundation Limited (EFL), together with three affected community members (a fisherman and 2 farmers) from Norochcholai, invoked jurisdiction of the Supreme Court under a Fundamental Rights application on the 22nd August 2016, against the only coal power plant in Sri Lanka. This case challenges the NCPP as it causes serious health, economic, and environmental impacts violating several provisions of the Constitution including Article 12 (right to equal protection of law), Article 14(1)(g) (right to occupation) and Article 14 (1)(h) (right to choose one's residence and freedom of movement). Moreover, EFL's Petition pleads that the NCPP's operations are contrary to Sri Lanka's international obligations towards emission reduction and environmental protection as stipulated in the Kyoto Protocol to the United National Framework Convention on Climate Change, The UN Framework Convention on Climate Change (UNFCC), Paris Agreement on Climate Change and others.

The NCPP poses irreversible grave impacts to the health, safety and livelihoods of surrounding communities and causes irreparable damage to the environment, both land and sea. Emissions cause multiple adverse impacts as the coal itself is toxic and burning of the coal releases greenhouse gases and toxins. The coal combustion produces residue such as fly ash (generated from coal combustion), bottom ash (deposited in the system) and boiler slag. These materials are hazardous to both human health and environmental sustenance as they contain heavy metals such as mercury, and radioactive nucleoids.

The impacts of the coal power plant not only affect those living in its immediate vicinity but pose the threat of harms to future generations as well.

Current status of the case
The Supreme Court issued a directive on the 24 March 2017, stating that EFL should partake in the discussion along with an independent Technical Review Committee (TRC) appointed by the Public Utilities Commission of Sri Lanka (PUCSL). The purpose was to review operations of all major power plants monitoring their environmental and social impacts. The CEB, Central Environmental Authority (CEA), North Western Province Provincial Environmental Authority (NWPEA) and community representatives from Norochcholai were other parties to this discussion. The TRC had made a decision to investigate issues pertaining to the NCPP first as it was the most critical out of all.

On the 01 February 2018, members of the committee signed an agreement titled 'Implementation Plan for the Mitigation of Environmental Impacts caused by the Norochcholai Coal Power Plant'. The agreement was formulated following several meetings and incorporated comments for the

above committee, organization and individuals. As per this agreement, a detailed action plan based on the above, was formulated and submitted to Court.
The said committee meets on a regular basis to monitor the implementation of the plan for the next two years.

The Supreme Court granted further time for all parties to enter into a settlement on the mitigatory environmental measures. The case is to be mentioned next on 04.10.2018.
// Extract

Annex 2: Estimation of Cost of Emission Control Technologies in the Coal Power Plant

A2.1 Technical Specifications of the Power Plant

The following technical specifications and operational parameters of the coal power plant are selected for the analysis, which primarily refer to the rated figures. Note that the actual operational data varies yearly and therefore may defer from the data used in the analysis, thus the results. However, the calculation procedure is valid and appropriate changes could be incorporated readily.

Table A2.1: Primary specifications

Parameter		Value	
Capacity		300	MW
Plant Factor		80	%
Properties of coal	Gross calorific value (GCV)	6,150	kcal/kg
		25.73	MJ/kg
	Sulphur content	1.00	% by wright
	Mercury content [30]	0.20	mg/kg
	Ash content	20	%
	Moisture (proximate analysis)	12	%
	Hydrogen (ultimate analysis)	3.8	%
Specific fuel consumption (SFC)		0.40	kg/kWh
Excess oxygen		6.0	%
Flue gas flow [37]		363.45	Nm^3/GJ (NCV)
Primary-controlled NOx emission factor [27], [38]		300	kg/TJ (NCV)
PM emission factor in the flue gas [27]		138	kg/t
Fugitive dust emission factor in the coal yard [35]		300	$g/m^2/yr$

Note: Mercury content used here refers to the average value reported for coal in South Africa, which is higher than the world's coal average value of 0.10 mg/kg [30].

Table A2.2: Derived performance parameters

Parameter	Value	
Annual electricity generation	2102.4	GWh/yr
Net Calorific value (NCV)	24.73	MJ/kg
Flue gas flow rate	8.99	Nm^3/kg fuel
	349.38	Nm^3/GJ (GCV)
	3,595.79	Nm^3/MWh
Primary-controlled NOx emission factor	825.42	mg/Nm^3
Annual coal Consumption	840.96	1000 t/yr
	2.80	t/kW/yr
SO_2 generation	16,819	t/yr
	8.0	kg/MWh
NO_X generation	6,240	t/yr
	2.97	kg/MWh
Hg generation	168.19	kg/yr
	80.0	mg/MWh
PM generation	116,052	t/yr
	55.2	kg/MWh
Fugitive dust generation (coal yard)	54.45	t/yr
	25.9	g/MWh

A2.2 Cost of Pollution Control: SO_2 [24], [25], [26]

- *Selected parameters*:

Technology:	Wet Flue Gas Desulfurization (FGD)
Pollutant removal efficiency:	95%
Operational life:	20 yrs.
Discount rate:	10%
Capital cost:	490 US$/kW
Annual O&M cost:	22.50 US$/kW/yr

- *Abatement cost estimates*:

SO_2 abatement:	15,978 t/yr 7.6 kg/MWh
Net present value of the cost:	681.56 US$/kW
Levelized abatement cost:	34.08 US$/kW/yr 639.83 US$/t SO_2 0.486 USCts/kWh = 0.851 Rs./kWh.

A2.3 Cost of Pollution Control: NO_X Error! Reference source not found., Error! Reference source not found., Error! Reference source not found., Error! Reference source not found.

- *Selected parameters*:

Technology:	Selective Catalytic Reduction (SCR)
Pollutant removal efficiency:	90%
Operational life:	20 yrs
Discount rate:	10%
Capital cost:	195 US$/kW
Annual O&M cost:	9.50 US$/kW/yr

- *Abatement cost estimates*:

NO_X abatement:	5,616 t/yr 2.67 kg/MWh
Net present value of the cost:	275.88 US$/kW
Levelized abatement cost:	13.79 US$/kW/yr
	736.64 US$/t NO_X
	0.197 USCts/kWh = 0.344 Rs./kWh

A2.4 Cost of Pollution Control: Hg [26], [30], [31]

- *Selected parameters*:

Technology:	Standard Actuated Carbon Injection (ACI)

Pollutant removal efficiency:	90%
Operational life:	20 yrs.
Discount rate:	10%
Capital cost:	21 US$/kW
Annual O&M cost:	0.30 US$/kW/yr

- *Abatement cost estimates*:

Hg abatement:	151.37 kg/yr 72.0 mg/MWh
Net present value of the cost:	23.55 US$/kW
Levelized abatement cost:	1.18 US$/kW/yr
	2,338,597.16 US$/t Hg
	0.017 USCts/kWh = 0.029 Rs./kWh

A2.5 Cost of Pollution Control: PM

A2.5.1 Technology Option 1: Dry Electrostatic Precipitation [27], [32], [33]

- *Selected parameters*:

Technology:	Dry Electrostatic Precipitation (ESP)
Pollutant removal efficiency:	99%
Operational life:	20 yrs
Discount rate:	10%
Capital cost:	120,000 US$/(m3/s) 119.86 US$/kW
Annual O&M cost:	12,500 US$/($m^3$/s)/yr 12.49 US$/kW/yr

- *Abatement cost estimates*:

PM abatement:	114,892 t/yr
Net present value of the cost:	226.19 US$/kW
Levelized abatement cost:	11.31 US$/kW/yr
	29.53 US$/t PM
	0.161 USCts/kWh = 0.283 Rs./kWh

A2.5.2 Technology Option 2: Fabric Filter [27], [32], [39]

- *Selected parameters*:

Technology:	Baghouse or Fabric Filter (FF) – Reverse air cleaned type with sonic horn enhancement
Pollutant removal efficiency:	99%
Operational life:	20 yrs

Discount rate:	10%
Capital cost:	78,000 US$/(m3/s) 77.91 US$/kW
Annual O&M cost:	30,000 US$/($m^3$/s)/yr 29.96 US$/kW/yr

- *Abatement cost estimates*:

PM abatement:	114,892 t/yr
Net present value of the cost:	332.98 US$/kW
Levelized abatement cost:	16.65 US$/kW/yr
	43.48 US$/t PM
	0.238 USCts/kWh = 0.416 Rs./kWh

A2.6 <u>Cost of Pollution Control: Fugitive Emissions (Coal Yard)</u>

Selected parameters:

Technology:	Wind fencing assisted by water mist system
Pollutant removal efficiency:	94% (Wind fencing – 70%; Water mist – 80%)
Dust emission factor:	300 mg/m^2/yr
Total exposed surface area:	181,500 m^2
Operational life:	10 yrs.
Discount rate:	10%
Total length of fence:	1,600 m
Height of fence:	20 m to 45 m
Capital cost - fencing:	11,540 US$/m (weighted average) 20.52 US$/kW
Capital cost - water mist system:	145,000 US$/unit; 4 units 1.93 US$/kW
O&M cost - fencing:	461,625 US$ (7.5% of the CAPEX) 1.54 US$/kW/yr
O&M cost - water mist system:	251,660 US$/yr 0.839 US$/kW

- *Abatement cost estimates*:

PM abatement:	51.18 t/yr
Net present value of the cost:	1,707.42 US$/kW
Levelized abatement cost:	37.07 US$/kW/yr
	21,745 US$/t PM
	0.053 USCts/kWh = 0.093 Rs./kWh