A QUANTITATIVE ANALYSIS OF INDUSTRIAL CARBON EMISSION AND STRATEGIES FOR CARBON REDUCTION

by

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CERTIFICATE OF APPROVAL

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Sadia Mohsin
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Dedicated

To

My Beloved Parents

ACKNOWLEDGEMENT

First of all the author would like to express her deepest sense of faith and gratitude to Almighty ALLAH, Who is Gracious to all.

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ABSTRACT

This study intends to estimate carbon emission from energy consuming sources at garments industries in Bangladesh and to represent some strategies for Greenhouse Gas (GHG) reduction i.e. CO_2e emission reduction. The thesis work has been carried out by collecting data from different garments industries in Bangladesh through field visit. The collected data has been verified and after analyzing all data, current GHG emission i.e. CO_2e emission from garments industries has been quantified. IPCC Tier 1 approach has been followed for quantifying GHG emission from direct onsite fuel combustion and Tier 2 approach has been applied for quantifying the emissions from purchased electricity.

After estimating the existing CO_2e emission, some cost effective carbon management techniques such as installation of VFD in compressor, installation of LED light instead of T5 and T8 fluorescent tube light, installation of EGB, installation of economizer in boiler, condensate recovery, auto blow down, setting of servo motor in sewing machine, switching off unnecessary light during day time, repairing air leakages, installation of G trap in steam iron, insulation of hot surfaces have been suggested to reduce the carbon emission at RMG sector.

The result of this study indicates that the garments industries emit about 0.89 kg/pc specific CO_2. By adopting different carbon reduction strategies the garments industries could cut their existing carbon emission by about 15.26% and thus the benchmark of specific CO_2 emission would be about 0.74 kg/pc. Besides this the garments industries could save about 12.61% energy and the benchmark of specific energy consumption would be11192 KJ/pc in average. Carbon reduction at garments industries will help to reduce national CO_2 emission of Bangladesh and it will ultimately contribute to reduce global warming. By taking carbon reduction measures, it is also possible to improve energy efficiency and cut cost at garments industries.

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ACRONYMS AND ABBREVIATION

CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CFCs	Chlorofluorocarbons
CH_4	Methane
CO_2e	Carbon Dioxide Equivalent
C_p	Specific Heat of Flue Gas
DoE	Department of Environment
EGB	Effluent Gas Boiler
EGB	Effluent Gas Boiler
ERU	Emission Reduction Unit
GCV	Gross Calorific Value
GEF	Grid Emission Factor
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KJ	Kilojoule
KWH	Kilowatt Hour
LED	Light-Emitting Diode
MJ	Mega Joule
MWH	Megawatt Hour
N_2O	Nitrous Oxide
NMVOCs	Non-Methane Volatile Organic Compounds
pc	Piece (unit of production)
PFCs	Perfluorocarbons
PPM	Parts Per Million
RMG	Readymade Garments
RMU	Removal Unit
SC	Specific Consumption

SF_6	Sulfur Hexafluoride
T_a	Ambient Temperature
tCO_2e	Ton Carbon Dioxide Equivalent
TDS	Total Dissolved Solid
T_f	Flue Gas Temperature
Ton	Metric Ton
UNFCCC	United Nations Framework Convention on Climate Change
VER	Verified Emission Reduction
VFD	Variable Frequency Drive

CHAPTER 1
INTRODUCTION

1.1 Background

Nowadays global climate change is the greatest concern. Fossil fuel combustion is the single largest source of anthropogenic greenhouse gas (GHG) emissions which is the dominant driver of global climate change. Greenhouse gas emissions from industries primarily come from burning fossil fuels for steam generation in boiler and captive power generation which results in climate change and global warming (Griffin et al., 2016). To control the dramatic growth of greenhouse gases and its related consequences, a broad set of carbon dioxide (CO_2) limiting strategies are needed. The strictness and extent of such strategies will play a significant role in decision making process regarding future investments in different energy technologies (Wahedi and Dadach, 2013).

According to the 2015 Energy Efficiency and Conservation Master Plan (EECMP), 47.8% of primary energy is consumed by the industrial sector in Bangladesh. The garments and textiles industries make up 27.8% of that share among all industrial sub-sectors (Haque, 2015). The readymade garment (RMG) industry is the leading export oriented manufacturing industry in Bangladesh which consumes more energy for process operation (Asif, 2017). The utilization of fossil fuel in manufacturing process results in a significant increase in CO_2 which is one of the foremost GHG (Wang et al., 2015).

Climate scientists have observed that CO_2 concentrations in the atmosphere have been increasing significantly over the past century, compared to the pre-industrial era level of about 280 parts per million (ppm) (Abdallah and El-Shennawy, 2013). Significant increases have also occurred in the levels of methane (CH_4) and nitrous oxide (N_2O). Greenhouse effect is caused by greenhouse gases that trap heat in the earth's atmosphere, – a natural phenomena that keeps the earth warm. A high concentration of GHG affects the earth's equilibrium making it out of balance, creating a dangerous rise in temperatures and extreme weather conditions. Unchecked global warming could affect most terrestrial eco regions. Increasing global temperature means that ecosystems will change; some species are being forced out of their habitats (possibly to extinction), because of changing conditions, while others are flourishing. Secondary effects of global warming, such as lessened snow cover, rising sea levels, and weather changes, may influence not only human activities but also the ecosystem. As people burn more fossil fuel for energy they add more carbon dioxide to the atmosphere. Carbon dioxide contributes more to the recent increase in greenhouse warming than any other gas as it persists in the atmosphere longer, as concentrations continue to rise. The increasing atmospheric carbon dioxide concentration is likely the most significant cause of the current warming (Supekar, 2015).

Only a systematic approach including a continuous improvement process could reduce the carbon footprint of garments industries (Jain, 2017). Increased energy efficiency would lead to decreased energy usage and thereby reduced GHG emissions (Khude, 2017). Some strategies for reducing carbon emission and improving energy efficiency contribute for reduction in energy consumption and process-related CO_2 emissions of RMG sector (Zahan et al., 2012).

In this study the CO_2 emission in garments sector has been quantified and the carbon management techniques have been analyzed by estimating the saving potential.

1.2 Objective of the Study with Specific Aim

The overall objective of the work presented in this thesis is to provide a technology-based perspective on the feasibility of significant reductions in CO_2 emissions in the garments sectors. The objectives of this study with specific aim are as follows:

I. To estimate baseline carbon emission from energy consumption at garments industries in Bangladesh.

II. To assess possible techniques for Greenhouse Gas reduction i.e. CO_2e emission reduction at RMG sector which will ultimately help to reduce global warming.

III. To estimate the carbon emission benchmark from the difference of the existing carbon emission and the emission reduction amount after adopting the proposed carbon reducing strategies. By taking carbon reduction measures, the garments industries could improve energy efficiency and cut cost.

1.3 Scope of the Study

The carbon emission i.e. Carbon Dioxide Equivalent (CO_2e) from readymade garments (RMG) sector has been quantified by conducting field survey in 10 garments industries. The scopes for estimating carbon emission are:

Scope 1: Direct emission from stationary combustion sources.

Scope 2: Indirect Emission from purchased electricity.

The boundaries of the study are as follows-

The greenhouse gases emission are considered for 3 major gases i.e. CO_2, CH_4 and N_2O. Total GHG emission has been expressed as carbon dioxide equivalent (CO_2e) emission. The GHG emission from Corporate Value Chain and mobile emission from transportation has not been considered in this study due to lack of necessary data at the factory management.

1.4 Outline of the Thesis

This thesis has been organized in 5 chapters. Chapter 1 is the introductory section which is intended to give a general introduction to the background of the work along with the objectives, aim and scope of the current study. Chapter 2 presents literature review. Chapter 3 includes the methodology and the detail of the work. Chapter 4 consists of result and discussion of the study. Chapter 5 contains conclusion of the study with recommendation for future work.

CHAPTER 2
LITERATURE REVIEW

2.1 General

In this chapter a brief description of carbon footprinting, climate change, baseline, benchmark and carbon reduction technologies have been presented. Several valuable works have been identified that deal with carbon emissions measurements, reduction/mitigation prospects, and industrial energy efficiency. Several studies on carbon emission has been done on Garments and Textiles Industry, Iron and Steel Industry, Chemical Sector, Food Industry, Cement Industry in China, the UK and in some Asian countries. In this chapter, different literatures on the carbon emission and energy consumption has been reviewed.

2.2 Carbon Footprint

Carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by the human activity or is accumulated over the life stages of a product. It includes direct emissions, such as those that result from fossil-fuel combustion in manufacturing, heating, and transportation, as well as emissions required to produce the electricity associated with goods and services consumed. In addition, the carbon footprint concept also often includes the emissions of other greenhouse gases, such as methane, nitrous oxide. Carbon footprint is expressed as carbon dioxide equivalent. Many companies and organizations are estimating the carbon footprint to assess their own contribution to the global temperature risings. An individual's, nations', or organization's carbon footprint can be measured by undertaking a GHG emissions assessment or other calculative activities denoted as carbon accounting (Bhautmage et al., 2015).

However in this study the carbon emission from stationary combustion source (direct emission) and purchased electricity (indirect emission) of garments industries has been quantified by undertaking GHG emission. Besides, the possible ways to reduce the carbon emission has also been identified.

2.3 Climate Change and Global Warming

Climate change may refer to a change in average weather conditions or in the time variation of weather within the context of longer-term average conditions. Climate change, also called global warming, refers to the rise in average surface temperatures on Earth. An overwhelming scientific consensus maintains that climate change is due primarily to the use of fossil fuels, which releases carbon dioxide and other greenhouse gases into the air. The gases trap heat within the atmosphere, which can have a range of effects on ecosystems, including rising sea levels, severe weather events, and droughts that render landscapes more susceptible to wildfires. Other human activities, such as agriculture and deforestation, industrialization, also contribute to the proliferation of greenhouse gases that cause climate change. In recent decades, changes in climate have caused impacts on natural and human systems across the globe. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate.

According to IPCC (2014), globally averaged combined land and ocean temperature data show an increase of 0.89°C over the period 1901-2012 (Figure 2.1).

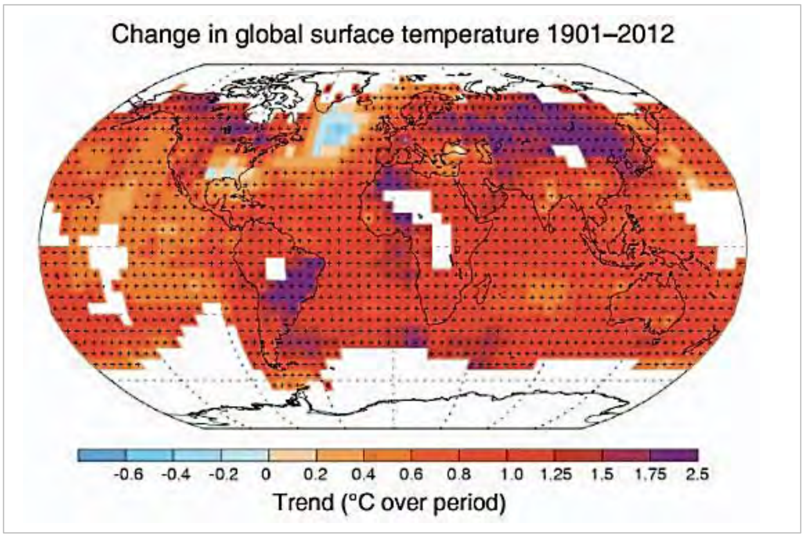


Figure 2.1: Climate Change Due to Rise in Surface Temperature (IPCC, 2014)

In the 5th Assessment Report of IPCC, CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification. Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system.

Limiting climate change will require substantial and sustained reductions of GHG emissions relative to the average from year 1850 to 1900, global surface temperature change by the end of the 21st century is projected to likely exceed 1.5°C (IPCC, 2014).

2.4 Greenhouse Effect

The greenhouse effect is somewhat similar to the process that goes on in a real greenhouse. The original concept of the greenhouse effect dates back to 1824 with Joseph Fourier. The glass of a greenhouse allows the sun's radiation in, which warms the ground inside, which in turn warms the air above the ground by long-wave (heat) radiation. The glass then acts like a barrier to keep the warm air inside from mixing with the cooler air outside the greenhouse.

The greenhouse gases in the atmosphere allow the sun's short wavelength radiation in, and because of the chemical properties of the gases, they do not interact with sunlight. But they do absorb the long-wave radiation from the earth and emit it back into the atmosphere, different from a greenhouse which does not allow the long-wave radiation to escape through the glass. The increase in trapped energy leads to higher temperatures at the earth's surface. This is called the greenhouse effect. The greenhouse effect is a foremost factor in keeping the Earth heartfelt because it keeps some of the planet's heat that would otherwise escape from the atmosphere out to space. In fact, without the greenhouse effect the Earth's average global temperature would be much colder and life on Earth as we recognize it would not be possible. The difference between the Earth's actual average temperature 14°C (57.2°F) and the expected effective temperature just with the Sun's radiation -19°C (-2.2°F) gives us the strength of the greenhouse effect, which is 33°C.

The most abundant greenhouse gases responsible for the greenhouse effect in the atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. These greenhouse gases keep the surface of the Earth approximately 60F warmer than we would expect without these gases present. Some human activities like the production and consumption of fossil fuels, use of various chemicals agriculture, burning bush, waste from incineration processes and other industrial activities have increased the concentration of greenhouse gases (GHG), particularly CO_2, CH_4, and N_2O in the atmosphere making them harmful. This increase in atmospheric GHG concentration has led to climate change and global warming effect, which is motivating international efforts such as the Kyoto Protocol, signing of Paris Agreement on climate change and other initiatives to control negative outcomes of the greenhouse effect. The contribution of a greenhouse gas to global warming is commonly expressed by its global warming potential (GWP) which enables the comparison of global warming impact of the gas and that of a reference gas, typically carbon dioxide.

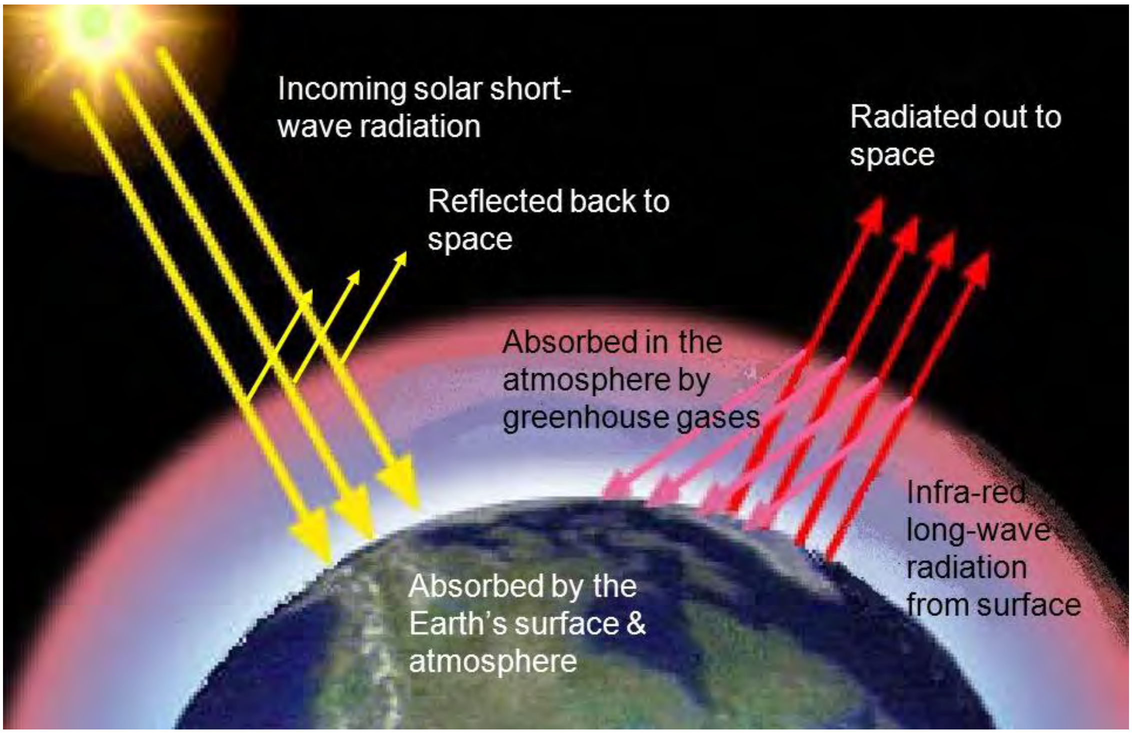


Figure 2.2: Greenhouse Effect (Kweku et al, 2017)

2.4.1 Global greenhouse gas emission by gas:

The percentages of different gases responsible for GHG emission are presented in Figure 2.3:

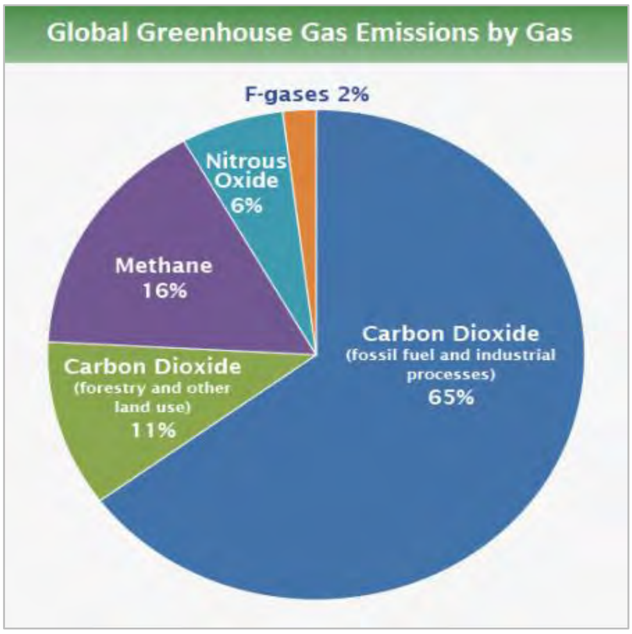


Figure 2.3: Global GHG Emission Percentage by Gas (IPCC, 2014)

At the global scale, the key greenhouse gases emitted by human activities are:

I. Carbon dioxide (CO_2): Use of fossil fuel primary source of CO_2. CO_2 can also be emitted from direct human-induced impacts on forestry and other land use, such as through deforestation, land clearing for agriculture, and degradation of soils.

II. Methane (CH_4): CH_4 emissions occur due to agricultural activities, waste management, energy use, and biomass burning.

III. Nitrous oxide (N_2O): Agricultural activities, such as fertilizer use, are the primary source of N_2O emissions. Fossil fuel combustion also generates N_2O.

IV. Fluorinated gases (F-gases): Industrial processes, refrigeration, and the use of a variety of consumer products contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

Among all greenhouse gases CO_2, CH_4 and N_2O are significant which are generally accounted for GHG emission estimation. The total GHG emission is presented as equivalent Ton of CO_2.

2.4.2 Global emissions by economic sector

Global greenhouse gas emissions can also be broken down by the economic activities that lead to their production. In the publication of IEA (2016), it has been found that two sectors produced nearly two-thirds of global CO_2 emissions from fuel combustion in 2014: electricity and heat generation, by far the largest, which accounted for 42%, while transport accounted for 23% (Fig 2.4.).

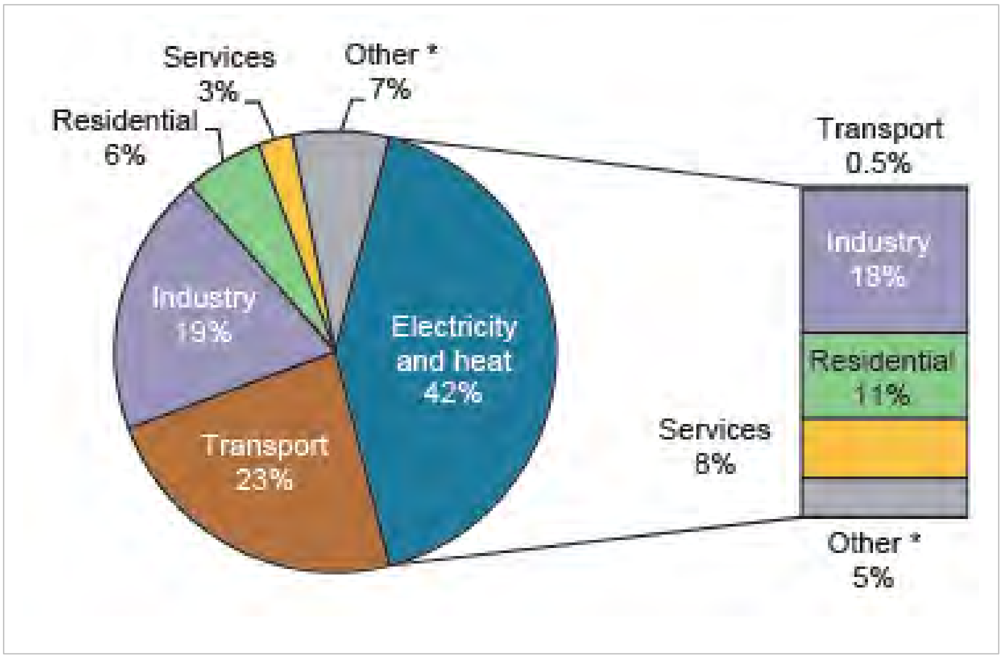


Figure 2.4: World CO_2 emissions from fuel combustion in 2014 (IEA, 2016)

* Other includes agriculture/forestry, fishing, energy industries other than electricity and heat generation, and other emissions not specified elsewhere.

2.4.3 Global Emission by Fuel

Boden et al. (2017) studied the global carbon emission from fossil fuel. The emission trend is presented below (Figure 2.5):

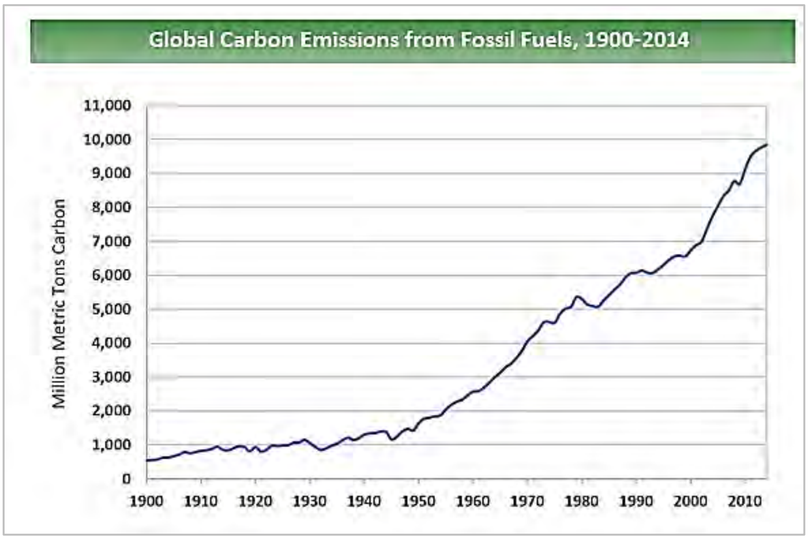


Figure 2.5: Global Carbon Emission from fossil fuel (Boden et al., 2017)

From the above figure, it could be seen that the growing world energy demand from fossil fuels plays a key role in the upward trend in CO_2 emissions. Since the Industrial Revolution, annual CO_2 emissions from fuel combustion have dramatically increased. The 2014 global fossil-fuel carbon emission estimate, 9855 million Ton of carbon, represents an all-time high and a 0.8% increase over 2013 emissions. The slight increase continues a three-year trend of modest annual growth under 2% per year.

Globally, liquid and solid fuels accounted for 75.1% of the emissions from fossil-fuel burning and cement production in 2014 (Figure 2.6).

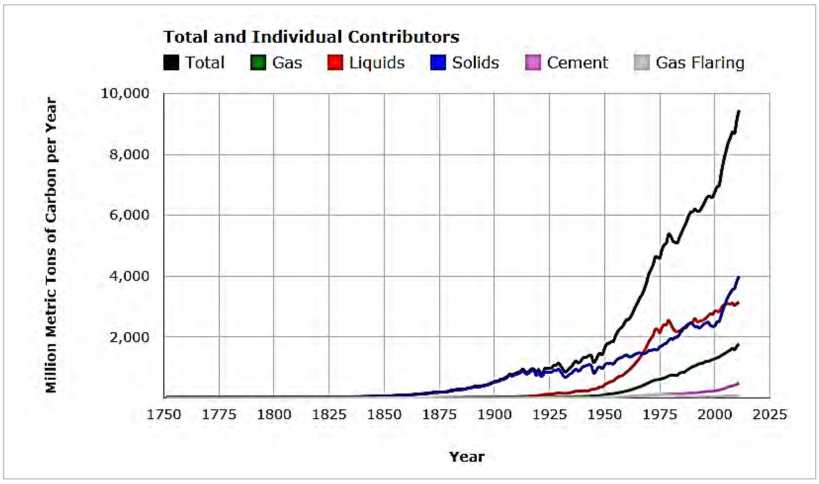


Figure 2.6: Fuel Shares in Global CO_2 Emission (Boden et al., 2017)

Combustion of gas fuels (e.g., natural gas) accounted for 18.5% (1823 million Ton of carbon) of the total emissions from fossil fuels in 2014 and reflects a gradually increasing global utilization of natural gas. Emissions from cement production (568 million Ton of carbon in 2014) have more than doubled in the last decade and now represent 5.8% of global CO_2 releases from fossil-fuel burning and cement production. Gas flaring, which accounted for roughly 2% of global emissions during the 1970s, now accounts for less than 1% of global fossil-fuel releases.

In this study greenhouse gas as equivalent CO_2 emission from industrial sector particularly garments industry has been quantifies with possible ways to reduce the CO_2 emission from the industries which help to reduce global GHG emission.

2.5 Baseline Emissions

A baseline is a line that is a base for measurement. Baseline emissions refer to the production of greenhouse gases that have occurred in the past and which are being produced prior to the introduction of any strategies to reduce emissions. The baseline measurement is determined over a set period of time, typically one year. Without the knowledge of baseline emissions, it is impossible to reliably judge the success of any remediation efforts. Baseline emission information is also valuable when nations or industries seek to negotiate with other jurisdictions to trade emissions so that both parties can meet their overall emission-reduction targets. The base year is a historical year which marks the transition from emissions estimates based on an inventory to modelling-based estimates of emissions volumes. In many countries the base year coincides with the latest year for which emissions inventory data are available. In other instances, there may be a gap of a few years between the latest year for which inventory data are available and the initial year for which projections are made. In this study the baseline carbon emission from energy use in ready-made garments (RMG) sector has been estimated.

2.6 Benchmarking

Benchmarking is a standard or point of reference against which things may be compared. It could also be defined as a measurement of the quality of an organization's policies, products, programs, strategies, etc., and their comparison with standard measurements, or similar measurements of its peers. Benchmarking is an external criteria against which the baseline data, observations have been compared and evaluated with the goal to improve.

The objectives of benchmarking are to:

I. Determine what and where improvements are called for;
II. Analyze how other organizations achieve their high performance levels, and
III. Use this information to improve performance.

Analyzing Specific Consumption (SC) is a criterion to identify benchmark. Specific Consumption gives a relationship between the CO_2 emission of a process and the production output from that process.

The carbon emission benchmark enables any organization to set their target for reducing the baseline emission. In this study the carbon emission benchmark of garments industries has been estimated from the difference of baseline carbon emission and tentative emission after implementing carbon reduction strategies.

2.7 Carbon Reduction Strategies

There are several carbon reduction technologies such as carbon capture and storage (CCS), energy efficiency techniques, and bioenergy. In this study the carbon reduction strategies has been presented based on energy efficiency techniques. By adopting energy efficient carbon reduction strategies at stationary combustion sources i.e. boiler, generator as well as electricity used in garments industries, it is possible to reduce GHG emission (as $eqCO_2$) significantly (USEPA, 2010). Some energy efficient techniques which could reduce carbon emission are repairing compressed air leakages, installing heat recovery in cloth driers, using servo motors for sewing machines instead of clutch plate motor in RMG factories, steam management using steam traps and condensate recovery, using flue gas economizer to preheat feed-water before entering boiler, changing lighting systems in RMG factories to light-emitting diodes (LEDs), insulation of pipes, valves and flanges etc..

2.8 Carbon Credit

A carbon credit is a permit or certificate allowing the holder to emit carbon dioxide or other greenhouse gases. “Carbon Credit” is, a unit of measure, the credit given to someone or an entity if they reduce their GHG emissions (Carbon Dioxide equivalents) by 1 unit. This is the flexibility mechanism provided through Clean Development Mechanism (CDM) under Kyoto Protocol. The issuance of carbon credits aims to reduce the emission of greenhouse gases into the atmosphere. There are two types of Carbon Credits:

I. Carbon Offset Credits (wind, solar, hydro and biofuels)
II. Carbon Reduction Credits

Carbon Offset Credits consist of clean forms of energy production, wind, solar, hydro and biofuels. Carbon Reduction Credits consists of the collection and storage of Carbon from our atmosphere through bio sequestration (reforestation, forestation), ocean and soil collection and storage efforts. Both approaches are recognized as effective ways to reduce the Global Carbon Emissions "crises" (Chonde, 2016). In this study carbon reduction credit has been considered for estimating CER and carbon price.

2.9 Carbon Trading

Carbon credit trading is one of the ways to control greenhouse emissions. Carbon emissions trading is a market-based approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants. A central authority (usually a governmental body) sets a limit or cap on the amount of a pollutant that may be emitted. The limit or cap is allocated or sold to firms in the form of emissions permits which represent the right to emit or discharge a specific volume of the specified pollutant. Firms are required to hold a number of permits (or allowances or carbon credits) equivalent to their emissions. The total number of permits cannot exceed the cap, limiting total emissions to that level. Firms that need to increase their volume of emissions must buy permits from those who require fewer permits (Afroj, 2016). This method of buying and selling is called carbon trading. This trading causes market forces to reduce overall carbon emissions. The idea of emissions trading with carbon credits relies heavily on the ability of polluters to reduce slowly but surely their emissions each year.

Under the Clean Development Mechanism, emission-reduction projects in developing countries can earn certified emission reduction (CER) credits. These saleable credits can be used by industrialized countries to meet a part of their emission reduction targets under the Kyoto Protocol. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction limitation targets. A CER is given by the CDM executive board projects in developing countries to certify that they have reduced greenhouse gases emissions by one Ton of carbon dioxide per year. The CDM is the main source of income for the UNFCCC Adaptation Fund, which was established to finance adaptation projects and programs in developing country Parties to the Kyoto Protocol that are particularly vulnerable to the adverse effects of climate change. The Adaptation Fund is financed by a 2% levy on CERs issued by the CDM.

Carbon is now tracked and traded like any other commodity. Kyoto Protocol provides various projects which can be undertaken and the credits generated through these projects are different from each other and have different importance. A removal unit (RMU) on the basis of land use, land use change and forestry activities such as reforestation, An emission reduction unit (ERU) generated by a joint implementation project and a certified emission reduction (CER) generated from a clean development mechanism project activity (Bhardwaj, 2013). Another type of greenhouse gas reduction unit is Voluntary Emission Reduction or Verified Emission Reduction (VER) which is a type of carbon offset exchanged in the voluntary or over-the-counter market for carbon credits. Verified Emission Reductions are usually certified through a voluntary certification process.

2.10 Literature Review of Past CO_2 emission work

Fayez et al. (2017) conducted a study on garments and textiles industries to identify the amount of energy consumption and estimation of GHGs for three consecutive years; 2013, 2014 and 2015 respectively, where 2013 was selected as the base year. This study revealed the scenario of energy consumption and greenhouse gas emission from garments and textiles industries in Dhaka, Bangladesh. Primary and secondary data collection method was applied during field study and data processing for garment and textile industries. Data Calculation was based on 2006 IPCC guidelines for national greenhouse gas inventories. Results shows that total energy consumption from all sources was 478.520 TJ in 2013 which emitted 47684 Ton of CO_2e GHGs. In 2014, consumption increased to 499.835 TJ which contributed 49839.65 Ton CO_2 e GHGs during that year. By the year 2015, both energy combustion and GHGs emission peaked to 58177.812 Ton CO_2e GHGs against 559.87 TJ fuel combustion. Overall, there were consecutive increasing trends of fuel combustion and GHGs emission from 2013 to 2015. Besides, natural gas was the highest energy sources on selected industries though its combustion emitted less GHG than electricity consumption. Furthermore, the rate of natural gas combustion decreased slightly when purchase electricity consumption increased by following years which had significant influence on increasing GHGs. This finding emphasized a great demand to control and reduce such growing trends of fuel consumption and GHGs emission. The study suggested that the industries have to find out potential energy saving opportunities, and alternate renewable energy sources.

Sarkar et al. (2015) has studied the trends of energy consumption and CO_2 emission in Bangladesh using the secondary data extracted from the World Development Indicators of the World Bank database. The results found that there is an increasing trend of total energy consumption and per capita energy consumption in Bangladesh from 1991 to 2012 where the total energy consumption has been increased nearly three times from 12.55 mtoe (million Ton oil equivalent) in 1991 to 33.17 mtoe in 2012. The total CO_2 emission was estimated by 57.07 mTon in 2011 which was increased by 140.67% compared to the 1991 emission of 15.94 mtoe. Thus, the CO_2 emission and per capita emission has also provided increasing trend over the period of 1991 to 2011.It has revealed that the growth of CO_2 emission found to be higher than the growth of GDP and energy consumption in Bangladesh. The yearly average growth of CO_2 emission is estimated to be 6.7% which is higher that the annual average growth of GDP and energy consumption, which are 5.25% and 4.77% respectively. This situation calls for serious attention of the country for reducing CO_2 emission. Therefore, government needs to develop a national mitigation plan/policy and promote the use and development of green technology, renewable energy and green growth for sustainable energy and environment in Bangladesh.

Ganesan et al. (2015) studied the specific energy consumption and CO_2 emission reduction analysis in textile industry. A detailed energy performance study was conducted in one of the textile industries to identify the energy saving potential. This study contributed to the reduction of specific energy consumption from 3041.3 kWh/Ton to 2867 kWh/Ton of the product. Overall, about 1029 MWh energy consumption was reduced which accounts 5.95% of the total energy consumed by the selected industry. The CO_2 emission reduction was 833 tCO_2/annum. The main aim of this study was not only to reduce the specific energy consumption but also to improve the energy performance of the equipment by adopting the various energy efficient technologies and energy conservation measures in order to control the Indian energy crises as well as to reduce CO_2 emission.

Barmaa et al. (2017) described in the journal about the amount of energy used in industrial boilers, ways employed to evaluate their energy efficiency, losses occurred and their causes, ways of waste heat recovery and minimizing heat loss using technologies, role of maintenance activities, and technical education to make people aware of the energy usage. A small improvement on the boiler efficiency will help to save a large amount of fossil fuels and to reduce CO_2 emission. It was found that a substantial amount of energy is wasted through high temperature flue gas or exhaust of the boiler. Also, some other unavoidable losses occur due to various reasons. However, waste heat could be recovered using different technologies as a useful form of energy such as electricity, heat, refrigeration effect, etc. The efficiency of the boiler can be improved by doing scheduled maintenance work, which helps to run a boiler at its highest efficiency.

Griffina et al. (2017) studied the opportunities and challenges to reducing industrial energy demand and carbon dioxide (CO_2) emissions in the Chemicals sector with a focus on the situation in the United Kingdom (UK). The improvement potential of various technological interventions was identified in terms of their energy use and greenhouse gas (GHG) emissions. Currently-available best practice technologies (BPTs) will lead to further, short-term energy and CO_2 emissions savings in chemicals processing, but the prospects for the commercial exploitation of innovative technologies by mid-21st century are far more speculative. A set of industrial decarbonisation 'technology roadmaps' out to the mid-21st Century were also reported, based on various alternative scenarios. It was found that the attainment of significant falls in carbon emissions over this period will depends critically on the adoption of a small number of key technologies [e.g., carbon capture and storage (CCS), energy efficiency techniques, and bioenergy], alongside a de-carbonization of the electricity supply.

Liu et al. (2014) studied the GHG emission of industrial process in Shenyang city, in the Liaoning province of China, using the 2006 IPCC greenhouse gas inventory guideline. Results showed that the total GHG emissions of industrial process increased from 1.48 Mt in 2004 to 4.06 Mt in 2009, except for a little decrease in 2008. The cement industry, and iron and steel industries, are the main emission sources, accounting for more than

90% of the total carbon emissions. GHG emissions in 2020 are estimated based on scenario analysis.

Tapan et al. (2013) examined CO_2 emissions from electricity and fuel consumption of different energy sources consumed in the Iron and Steel Industry sector in South Asia. The study found that CO_2 emissions vary across sectors in countries in which the study was conducted. For instance, while in Bangladesh CO_2 emissions are primarily caused by electricity generation, in India the majority of CO_2 emissions are originated from coal. On the contrary, CO_2 emissions in Nepal are mostly generated through other fuels such as Charcoal, Diesel and Kerosene. This study provided some policy recommendations, which could help to reduce CO_2 emissions in the Iron and Steel Industry sector in the South Asian region.

Zhu and Hu (2016) studied the Low-Carbon and Environmental Protection of Textile and Garment in China. For the pollution problem in China's textile and garment industry, the author particularly analyzed the pollution of the textile and garment industry mainly occurred in the process of textile and clothing production and sales in this article. Finally, the author put forward detail measure to control the pollution from the two aspects and advocates the concept of low-carbon environmental protection and green lifestyle.

CHAPTER 3
METHODOLOGY AND DATA COLLECTION

3.1 General

This chapter presents the method of quantifying carbon emission and carbon reduction strategies applicable for garments industries. The data collected from different garments industries such as fuel consumption, electricity consumption, production capacity etc. has also been presented in this chapter.

3.2 Protocol of Carbon Emissions

To measure the carbon emissions, '2006 IPCC Guidelines for National Greenhouse Gas Inventories' has been followed. The Guidelines estimate carbon emissions in terms of the types of gases that are emitted. During the combustion process, most carbon is immediately emitted as CO_2. However, some carbon is released as carbon monoxide (CO), methane (CH_4) or non-methane volatile organic compounds (NMVOCs). In the case of fuel combustion, the emissions of these non-CO_2 gases contain very small amounts of carbon compared to the CO_2 estimate. The major greenhouse gases i.e. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) has been considered during estimating GHG emission from stationary combustion sources and purchased electricity, since the amount of other greenhouse gases emission quantity is negligible.
There are three Tiers presented in the *2006 IPCC Guidelines* for Greenhouse gas estimating emissions.

Tier 1: It is top-down average emission factor approach. The Tier 1 method is fuel-based, since emissions from all sources of combustion can be estimated on the basis of the quantities of fuel combusted and average emission factors. Tier 1 emission factors are available for all relevant direct greenhouse gases.

For CO_2, emission factors mainly depend upon the carbon content of the fuel. Combustion conditions are relatively unimportant. Therefore, CO_2 emissions can be estimated fairly accurately based on the total amount of fuels combusted and the averaged carbon content of the fuels. The CO_2 emission factors is presented in IPCC (2006) guideline. Emission factor for CO_2 is in unit of kg CO_2/TJ on a net calorific value basis and reflect the carbon content of the fuel and the assumption that the carbon oxidation factor is 1. However, emission factors for CH_4 and N_2O for different source categories differ due to differences in combustion technologies applied in the different source categories. Default emission factors has been established using the expert judgment of a large group of inventory experts and are still considered valid.

Tier 2:_It is Mass balance approach. In the Tier 2 method, emissions from combustion are estimated from similar fuel statistics, as used in the Tier 1 method, but country-specific emission factors are used in place of the Tier 1 defaults. Since available country-specific emission factors might differ for different specific fuels, combustion technologies or even individual plants, activity data could be further disaggregated to properly reflect such disaggregated sources. If these country-specific emission factors indeed are derived from detailed data on carbon contents in different batches of fuels used or from more detailed information on the combustion technologies applied in the country, the uncertainties of the estimate should decrease, and the trends over time can be better estimated. In case of indirect emission from purchased electricity Tier 2 approach is applicable by using country-specific emission factor.

Tier 3: It is rigorous bottom-up approach. Tier 3 relies on the rigorous assessment of emissions from individual sources using a bottom-up approach, and requires both process infrastructure data and detailed production accounting data. It may also include actual measurement work as well. The results are then aggregated to determine the total emissions.

3.3 Choice of Method

In general, emissions of each greenhouse gases from stationary sources are calculated by multiplying fuel consumption by the corresponding emission factor (equation 3.1). Fuel consumption in mass or volume units is first converted into the energy content of these fuels.

Tier 1 approach is followed for estimating carbon emission from direct onsite fuel combustion at different garments industries in Bangladesh. Greenhouse gas emission has been calculated for major gases i.e. CO_2, CH_4 and N_2O by using default emission factor following Tier 1approach of IPCC 2006 guideline. The default emission factor of IPCC

(2006) guideline has been used for stationary combustion in calculating GHG emission of readymade garments manufacturing industries. The emission of individual gases i.e. CO_2, CH_4 and N_2O are obtained by multiplying the fuel consumption with density of fuel, net calorific value of fuel and emission factor of individual gases. The value of CH_4 and N_2O emission is converted from kg CH_4 and kg N_2O to kg CO_2e using the 100-year Global Warming Potential (GWP). The GWP of different greenhouse gases has been retrieved from IPCC 4th assessment report and given below in Table 3.1.

Table 3.1: Global Warming Potential of Greenhouse Gases (IPCC, 2007)

Name of Gases	Chemical Formula	100-Year GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

The indirect emission from purchased electricity consumption are measured following Tier 2 approach by using country-specific emissions factors i.e. national grid emission factor of Bangladesh. According to Department of Environment (DoE) of Bangladesh, the grid emission factor is 0.67Ton CO_2/MWH which is calculated as per tool to calculate the emission factor for electricity system (DoE, 2013).

3.4 Equipment Required for the Study

In this study the following equipment have been used:

- Temperature Gun
- Combustion Analyzer
- Digital Multi meter
- Ultrasonic Leak Detector

3.5 Different Steps of the Study

The whole study could be segregated at 3 main steps i.e. walk through and data collection, data verification, data crunching and calculation. The steps are presented in figure 3.1 and details of each steps are given below.

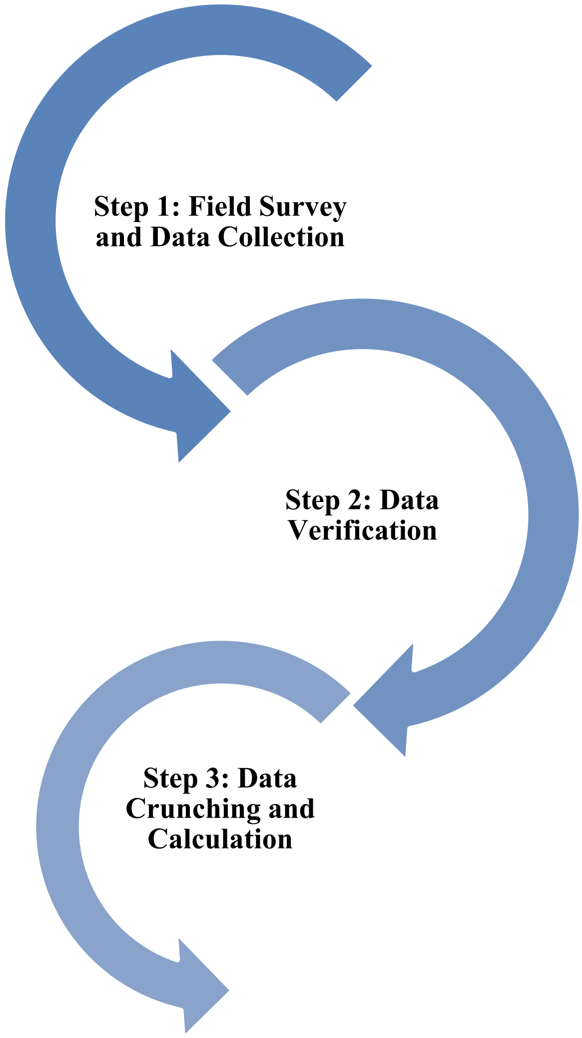


Figure 3.1: Work Steps

3.5.1 Field Survey and data collection

This study has been carried out by collecting data from 10 different garments industries which are located at Gazipur, Savar, Narayangonj and Chattogram. The data has been collected through field visit at those industries to identify the CO_2 emission sources and assess possible opportunities to reduce CO_2 emission as well as to save energy. The primary data collected from the industries include but not limited to fuel and electricity consumption data, production data and information about existing production process of the industries etc. During field visit, stack air emission of stationary combustion unit i.e boiler, generator etc. has been measured for different parameters like CO, CO_2, SO_2, NO, O_2 flue temperature etc. using combustion analyzer which is required for analyzing combustion efficiency. The temperature of hot bare surfaces has been measured by temperature gun to know whether or not insulation is required. Beside this, the air leakage in compressed air lines has been checked with ultrasonic leak detector by random sampling and TDS of blow down water has been measured by digital Multimeter.

Some secondary data have also been used in this study such as net calorific value of fuel, Emission Factor of CO_2, CH_4 and N_2O has been obtained from IPCC 2006 guideline. The National Grid Emission Factor of Bangladesh has been collected from Department of Environment (DoE) and Direct Global Warming Potential is found in IPCC guideline. During field visit the consumption data of purchased electricity and fuel have been collected from the electricity and gas bill of the industry as well as from checking their internal record book.

During field visit at different garments industries it has been found that the main production process flow of the garments industry is as below:

Cutting > Sewing > Finishing

Energy used in these sections from where CO_2 is emitted are listed below (Table 3.2):

Table 3.2 Energy Used in Garments Industries Which Emit CO_2

Name of Production Section	Energy Source which emits CO_2
Cutting	Electricity from Generator or Grid is used to run cutting machines
Sewing	Electricity from Generator or Grid is used to run sewing machines
Finishing	Steam from Boiler is used to operate steam iron and Electricity from Generator or Grid is used in electric iron and compressed air generation.

The main products of the visited garments industries are woven garments. The consumption of fuel, electricity and production capacities of garments factories are presented below in below Table 3.3.

Table 3.3 Production Capacity, Fuel and Electricity Consumption Data

No. of Visited Factories	Location	Production Capacity (Piece)	Electricity Consumption (KWH)	Natural Gas Consumption (m^3)	Diesel Consumption (Liter)	Other Fuel Consumption
1	Chattogram	6016156	6,630,126	-	14,915	-
2	Chattogram	7301521	13,338,606	-	33,647	-
3	Savar	3392000	247,822	1,558,584	59,526	-
4	Gazipur	1109897	115,949	-	40,080	570,490 (CNG in m3)
5	Gazipur	18720000	-	4,786,490	751,761	-
6	Chattogram	5543959	2,334,435	195544	317400	-
7	Narayangonj	9184631	998,082	3,736,549	87617	-
8	Chattogram	1903254	523,570.84	593555	585	-
9	Chattogram	2870283	2,157,390	194231	125	-
10	Chattogram	13478496	2,180,000	7,899,964	-	-

- Note: The sign “-” means no consumption

3.5.2 Data verification

The collected data has been verified. If any data is missing or need any clarification regarding the data then communication has been made with factory personnel to gather accurate information.

3.5.3 Data crunching and calculation

To estimate direct CO_2 emission from the stationary combustion sources (i.e. boiler, generator) as well as indirect emission from purchased electricity, the information and data collected from the field visit have been analyzed and several calculation have been done to find out suitable technique for minimizing the CO_2 emission. From the collected data, the annual CO_2 emission, possible energy savings opportunities, CO_2 reduction potential and payback period have been calculated as follows:

i. Direct Emission: GHG emission as Carbon dioxide equivalent (CO_2e) emission from stationary combustion has been calculated by analyzing the fuel/energy consumption data, properties of fuel, global warming potential and emission factor following 2006 IPCC Guidelines for National Greenhouse Gas Inventories for direct emission from onsite Stationary Combustion.

$$Emissions\ GHG,_{fuel} = Fuel\ Consumption_{fuel} * Emission\ Factor\ GHG,_{fuel} \ldots\ldots\ldots\ldots(3.1)$$

Where:

Emissions GHG, $_{fuel}$ = emissions of a given GHG by type of fuel (kg GHG)

Fuel Consumption $_{fuel}$ = amount of fuel combusted (TJ)

Emission Factor GHG, $_{fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ). For CO_2, it includes the carbon oxidation factor, assumed to be one.

To calculate the total emissions by gas from the source category, the emissions as calculated in Equation 3.1 are summed over all fuels:

Total Emissions by Greenhouse Gas

$$Emissions,_{GHG} = \sum_{fuel} Emissions\ GHG, fuel \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

ii. Indirect Emission:_GHG emission expressed as CO_2e from purchased electricity is calculated following below equation:

*Emission, CO_2e =Grid Electricity Consumption X Grid Emission Factor (GEF)…… (*3.3)

Where GEF of Bangladesh is 0.67Ton CO_2/MWH

iii. The fuel and energy has been calculated by following the below formulas (Krishnanunni et al., 2012).

Fuel saving is calculated from the consumption or loss of heat/energy, calorific value of fuel and annual working time.

AnnualFuel/ Energy Saving= Annual Heal Loss (KJ/year)/ GCV of Fuel ………..(3.4)

*Heat loss in dry flue gas = [m * Cp * (T_f- T_a)*]……….....................................(3.5)

Where, m is the mass of dry flue gas, C_p is the specific heat of flue gas, T_f is the flue gas temperature and Ta is the ambient temperature and GCV is Gross Calorific Value of Fuel.

iv. Fundamentally, specific consumption (SC) is a ratio of resource input and production output.

SC = Resource Consumed/ Production Output……….……(3.6)

v. Boiler efficiency could be obtained from below equation:

$$Boiler\ Efficiency = \frac{Steam\ Flow\ Rate \times (Steam\ Enthalpy - Feed\ Water\ Enthalpy)}{Fuel\ Firing\ Rate \times Gross\ Calorific\ Value}\ X100 \text{..(3.7)}$$

vi. The financial saving and payback period has been calculated by following the below formulas Annual Financial saving is calculated from fuel/energy saving per year and fuel/energy cost.

Annual Financial Saving= Annual Fuel Saving X Fuel Cost…………………………..(3.8)

vii. Simple Payback Period is calculated from the investment and financial saving of any carbon management technique (Gorshkov et al., 2018).

$$Payback\ Period\ = \frac{Investment\ (BDT)}{Saving\ (BDT/year)} \text{ ………………………………….(3.9)}$$

CHAPTER 4
RESULTS AND DISCUSSION

4.1 General

Analyzing the data and based on calculation of carbon emission at garments industries, possible carbon management techniques with opportunities for energy efficiency improvement and cost saving potential in a certain payback period have been presented in this chapter. It has been identified that the major carbon emission source of the garments industries is the fuel combusted in generator for electricity generation and fuel combusted in boiler for steam generation and grid electricity. In this study current carbon emission i.e. baseline emission of garments industries and carbon emission after adopting carbon reduction strategies i.e. benchmark has been estimated after analyzing the collected data and based on some calculation following IPCC guideline and some published journals. Besides carbon reduction there is an opportunity of saving energy at garments industries by adopting the carbon reduction strategies.

4.2 Existing Carbon Emission and Energy Consumption Baseline

The garments industry is extremely energy-intensive sector. The production of garments associated with significant CO_2 emissions which occurs due to burning fossil fuel for power generation and steam production. Carbon dioxide is also emitted indirectly from purchased electricity. By adopting the carbon reduction strategies/ technologies the garments industry could reduce their CO_2 emission and save energy.

By observing the process operation and utility part of different garments industries and after analyzing the collected data of field visit it has been found that the garments industries emit annually about 0.89 kg/pc specific CO_2 in average. The existing carbon emission baseline of individual garments factories is presented in Figure 4.1.

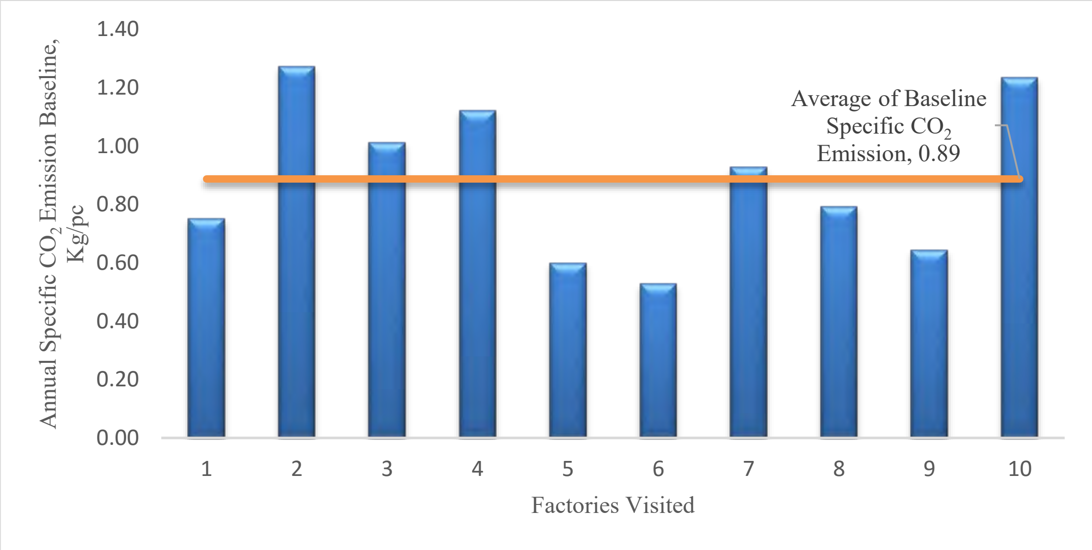


Figure 4.1: Existing Specific Carbon Emission Baseline at Different Garments Industries

From the above figure it could be seen that there is a fluctuation in CO_2 emission from different garments industries because different types of energy sources i.e. fuel, electricity are used in those factories whose emission factors differ from each other. Moreover some factories has already taken some carbon reduction measures which reduces their specific carbon emission.

It has been also observed that for process operation and utility purpose the garments industries consume energy in the form of fossil fuel and purchased electricity. The baseline specific energy consumption at garments industries is given below (Figure 4.2):

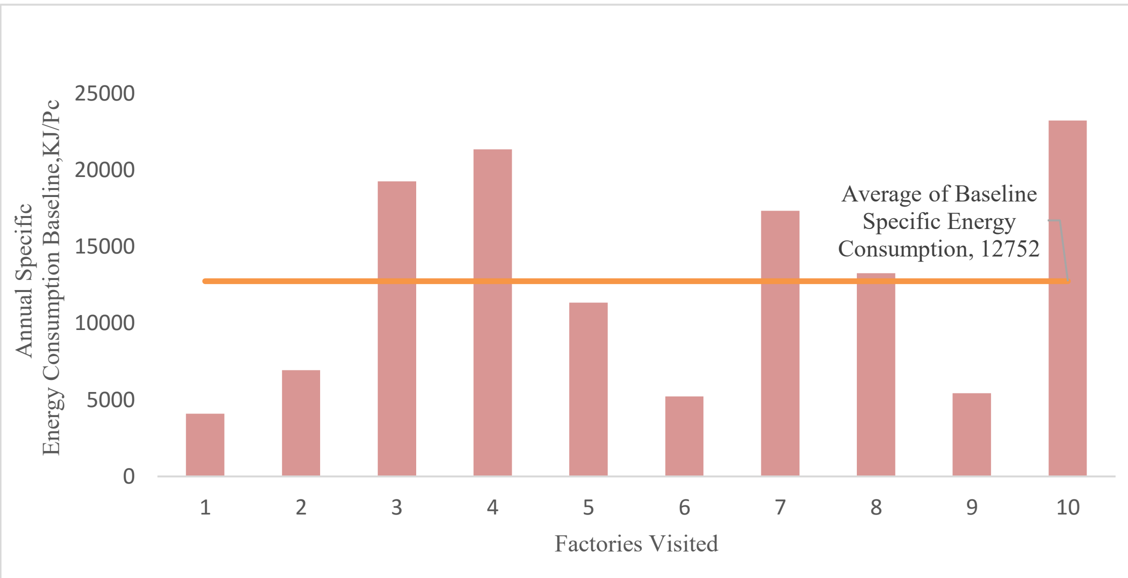


Figure 4.2 Existing Specific Energy Consumption Baseline at Different Garments Industries

From the graph it could be seen that the annual specific energy consumption of garments industries is maximum 23252KJ/pc, minimum 4082 KJ/pc and average 12752 KJ/pc depending on the production capacity and already implemented energy saving measures.

4.3 Key Carbon Reduction Strategies

The key carbon reduction strategies applicable for garments industries are discussed below:

4.3.1 Installation of effluent gas boiler (EGB)

The exhaust temperature of the gas generator is around 500°C which is released to the atmosphere through chimney. This waste heat of gas generator can be utilized to run an Effluent Gas Boiler (EGB). Installing an EGB will meet the demand of steam for process without using any additional fuel. Thus by installing EGB /Waste Heat Recovery Boiler the industries could reduce CO_2 emission due to no combustion of fossil fuel (Figure 4.3).

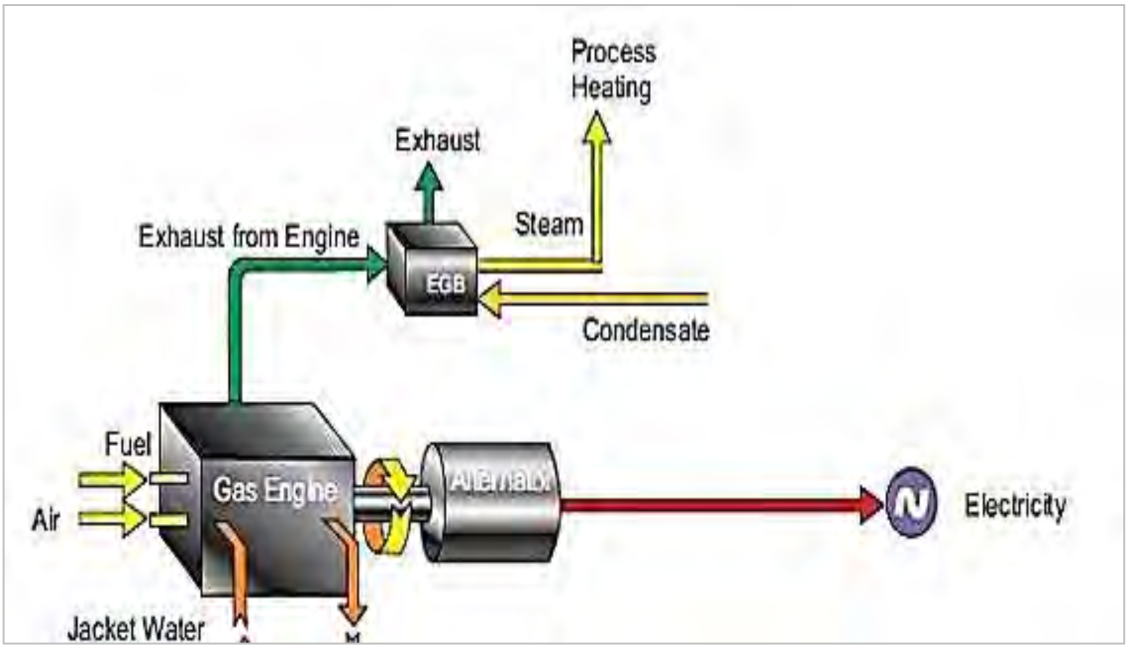


Figure 4.3: Heat Recovery from Gas Generator by Installing EGB

4.3.2 Flue gas heat recovery from boiler by installing economizer

Flue gas emitted from boiler contain high temperature ranges from 200 to 350 °C. Typical heat balance of boiler is presented in below (Figure 4.4):

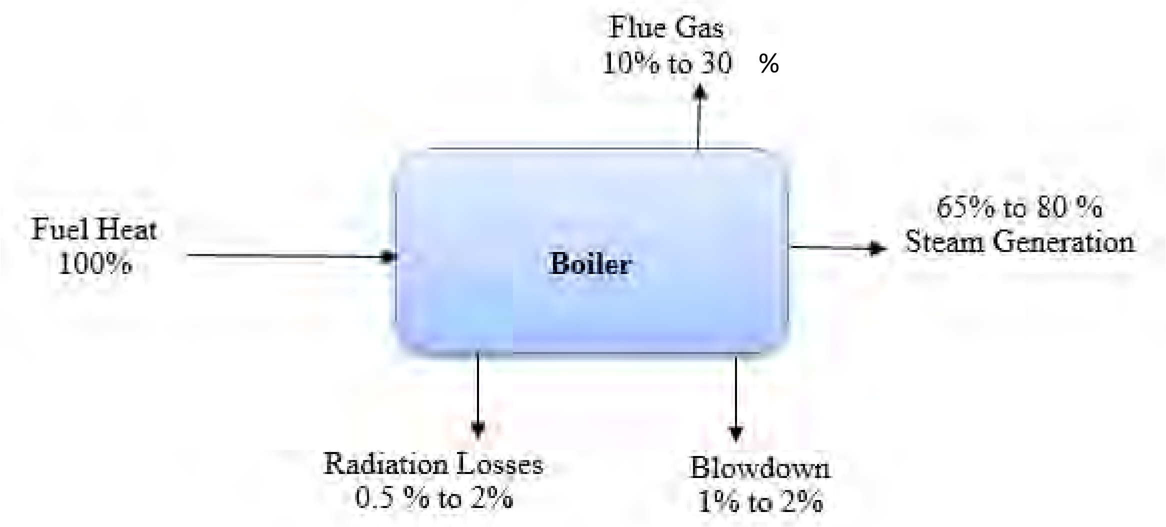


Figure 4.4: Typical Heat Balance of Boiler (Barmaa et al., 2017)

The heat of flue gas should be recovered and used locally and as directly as possible. Waste heat of flue gas may be put to further use for heating process water, for water heating, for preheating combustion and drying air or as space heating. In case of boilers of garments industries, it is advisable to use an economizer for preheating feed water.

Economizers is basically tubular heat transfer surface used to preheat boiler feed water before it enters the steam drum or furnace surfaces. Economizers also reduce the potential of thermal shock and strong water temperature fluctuations as the feed water enters the drum or water walls. An Economizer performs two functions, it reduces stack temperature and also heats boiler feed water. A practical rule of thumb is that for every 40°F (22°C) reduction in the stack temperature, a corresponding 1% of increase in efficiency occurs. On the other side, an increase of approximately 1% in efficiency is expected for each 11°F (6°C) rise in feed water temperature. Using economizer with boiler reduce CO_2 emission by saving fuel for heating water (Figure 4.5).

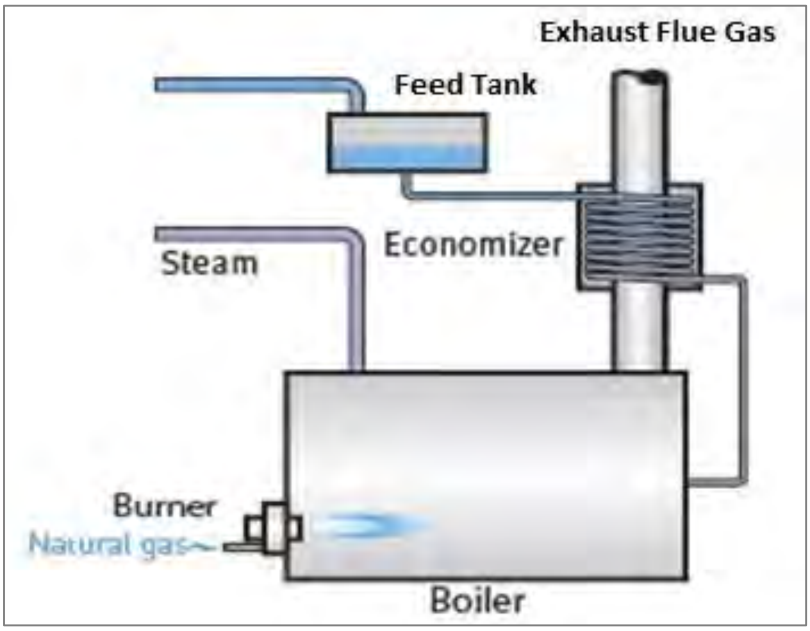


Figure 4.5: Working Process of a Boiler with Economizer

4.3.3 Installation of G trap in steam iron

The function of G trap is to capture steam and pass only condensate in condensate line. Installing G trap in individual steam iron of garments factory, it is possible to restrict steam to go inside the steam irons when steam is actually not required for cloth pressing. The fact is when operators fold the cloth (almost 40% time of total operating time) the iron remains idle. At that idle time the steam going inside the iron and directly going to condensate return line. By installation of G-trap the factory could save this huge amount of steam and heat and thus carbon emission could be reduced (Figure 4.6).

Figure 4.6: Installation of G Trap in Steam Iron Line

4.3.4 Condensate recovery

Condensate is the liquid formed when steam passes from the vapor to the liquid state. In a heating process, condensate is the result of steam transferring a portion of its heat energy, known as latent heat, to the product, line, or equipment being heated. By installation of condensate recovery system (Figure 4.7) and returning the condensate back to the feed water tank the factory can reduce a lot of fuel and increase boiler performance as well.

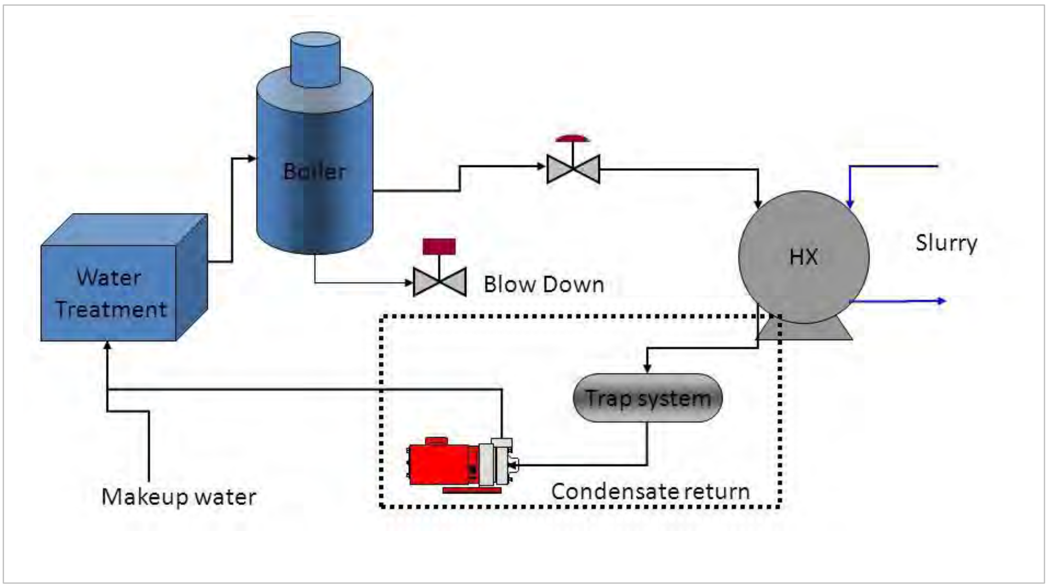


Figure 4.7: Condensate Return System

Most condensate is returned to boiler feed water tank at relatively hot temperature (typically 130 to 225 °F), compared to the cold makeup water (50 to 60 °F) that must be heated. Thus less heat is required for boiler feed water which enable the factory for reducing carbon emission. Condensate line return is applicable to all boiler types that do not already include return of hot condensate. The larger the unit and the hotter the condensate return, the more benefit will accrue.

Returning hot condensate to the boiler makes sense for several reasons besides carbon reduction. As more condensate is returned, less makeup water is required, saving fuel, makeup water, chemicals and treatment cost. Less condensate discharged into a sewer system reduces disposal cost. Return of high purity condensate also reduces energy losses due to boiler blow down.

4.3.5 Install auto blow down system

Boiler blow down is the removal of water from a boiler. Its purpose is to control boiler water parameters within prescribed limits to minimize scale, corrosion, carryover, and other specific problems. Blow down is also used to remove suspended solids present in the system. These solids are caused by feed water contamination, by internal chemical treatment precipitates, or by exceeding the solubility limits of otherwise soluble salts. Blow down are generally two type- Manual blow down and Automatic blow down.

With manual control of blow down, there is no way to determine the concentration of dissolved solids in the boiler water, nor the optimal blow down rate. Operators do not know when to blow down the boiler or for how long. Likewise, using a fixed rate of blow down does not take into account changes in makeup and feed water conditions, or variations in steam demand or condensate return. Some disadvantages of manual blow down are mentioned below:

- Huge heat loss
- Sudden pressure drop of steam
- Frequent requirement of de-scaling of boiler
- Scale deposits on tube and surfaces
- Higher chemical consumption
- Wastage of fuel and water
- Possibility of under or excess blow down

An automatic blow down-control system optimizes blow down rates by regulating the volume of water discharged from the boiler in relation to the concentration of dissolved solids present. The Auto blow down system is presented in Figure 4.8:

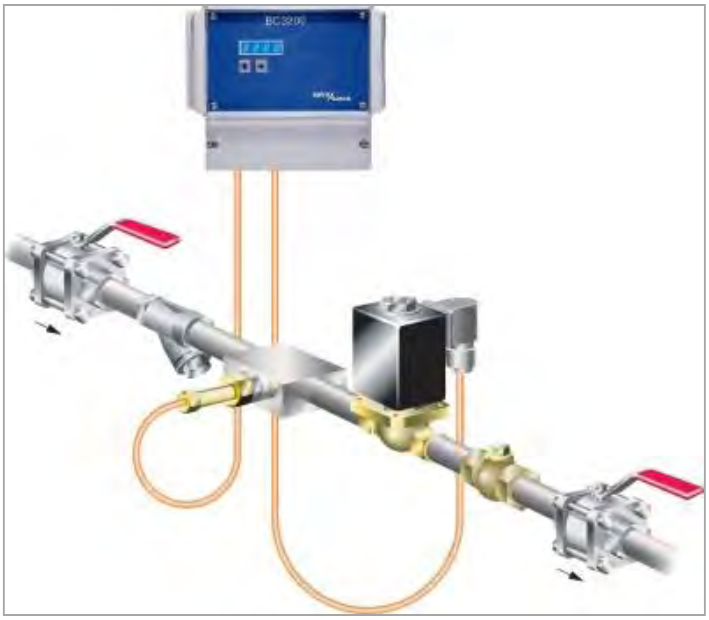


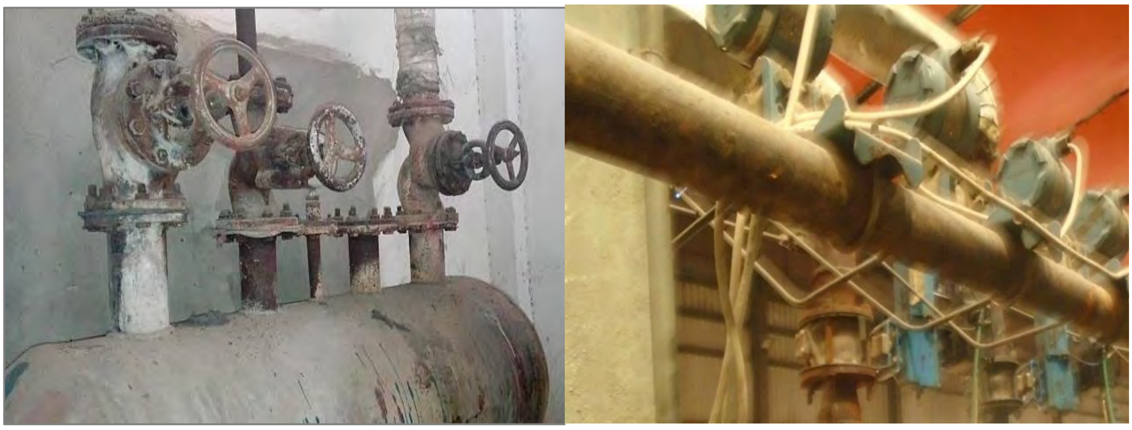
Figure 4.8: Auto Blow down System

By installing auto blow down system it is not needed to hold the dissolved solid for 4-5 hrs. It reduces scale formation in tubes as well as save huge amount of water, fuel and money as well. Automatic blow down control systems minimize the excess blow down which save energy and reduce carbon emission from the industrial boiler.

4.3.6 Insulation of boiler hot surface and steam distribution lines

Insulation is any material that is employed to restrict the transfer of heat energy. It can generally be categorized as either mass or reflective type depending on whether it is aimed at reducing conductive or radiative heat transmission, respectively. Properly applied insulation can result in large savings in energy losses depending on type, thickness, and condition of the existing insulation. Insulation is an important feature of boiler and steam distribution line.

Uninsulated steam distribution and condensate return lines are a constant source of wasted energy. The figures shows typical heat loss from uninsulated steam distribution lines. Insulation can typically reduce energy losses by 90% and can reduce carbon emission. Any surface over 120°F should be insulated, including boiler surfaces, steam and condensate return piping, feed water tank, steam header, valves and fittings. During field visit some hot surfaces have been identified which require insulation (Figure 4.9).



Un-insulated Steam Header and valves Un-insulated Steam Line

Figure 4.9: Some Hot Surfaces where Insulation is Required

To estimate the required hot surface of boiler and steam distribution line for insulation, it is necessary to know the boiler efficiency. For estimating boiler efficiency flue gas analysis has been performed to measure the concentration of CO, CO_2, SO_2, O_2, NO and flue temperature.

The heat losses from hot bare surfaces are estimated by using the following chart (Figure 4.10)

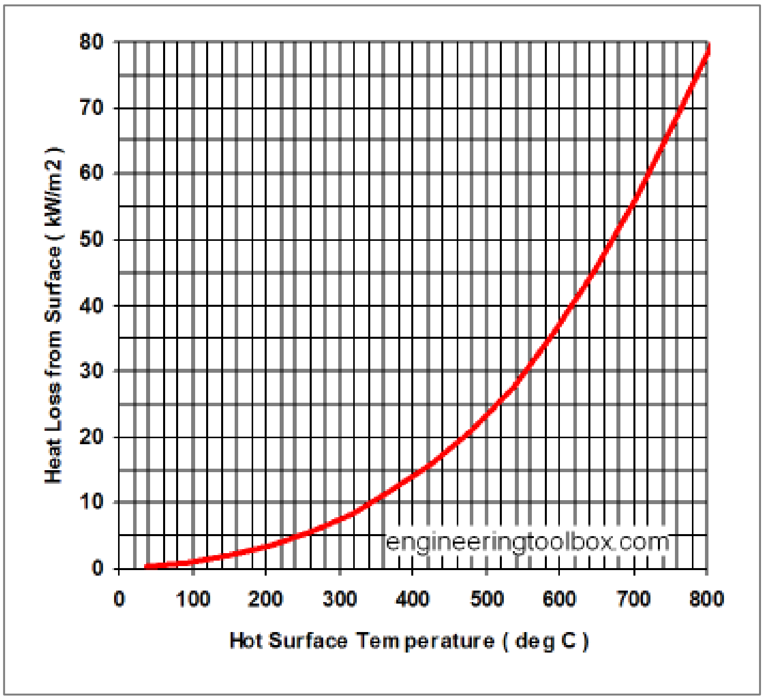


Figure 4.10: Diagram of Heat Loss from Hot Surfaces (The Engineering Toolbox)

It is required to insulate the hot bare surfaces of boiler, steam and condensate lines properly. Ways of proper insulation is presented in Figure 4.11:

Figure 4.11: Way of Proper Insulation

4.3.7 Installation of VFD in compressor

A large portion of the operating time of air compressor is at partial load. This is a very inefficient system of energy use in compressor. In this situation VFD can be installed to control the air discharge as well as speed of motor drive of the compressor.

A typical compressor application setup uses a direct electrical supply to power a motor, which then runs the compressor. The motor runs at a continuous speed regardless of the requirements placed on it by the compressor because the power supply is constant. The compressor uses the energy output it needs from the motor; the rest is wasted. If the motor is controlled by a Variable Frequency Drive (VFD), the frequency of the electricity powering the motor and hence the speed of the motor can be regulated according to the demands of the application. If less power is required from the motor at certain points in a process, then the drive adjusts the electrical frequency, slowing the motor. The aim of installing VFD is to ensure that the motor only generates enough energy to power the compressor and no more energy wastage. It is known that for generating electricity carbon-dioxide is emitted in environment. Thus installing VFD will reduce carbon emission by lowering the electrical energy requirement (Figure 4.12).

Figure 4.12: A Compressor with VFD

4.3.8 Repairing compressed air leakages

Compressed air leakage test has been conducted by random sampling of compressed air line, fitting and valves by using ultrasonic leak detector (Figure 4.13). During the assessment, several leakages have been found in different places of compressed air line such as air nozzle, pipe joint, valves etc. Compressed air is an expensive utility. It consumes huge electricity to generate compressed air and thus emit carbon dioxide. By repairing the leakage in compressed air line it is possible to reduce carbon emission by saving energy.

Figure 4.13: Air Leakage Found During Compressed Air Leak Test

The loss of compressed air through leakage (air volume) could be obtained from the Figure 4.14 by knowing the air pressure and orifice size.

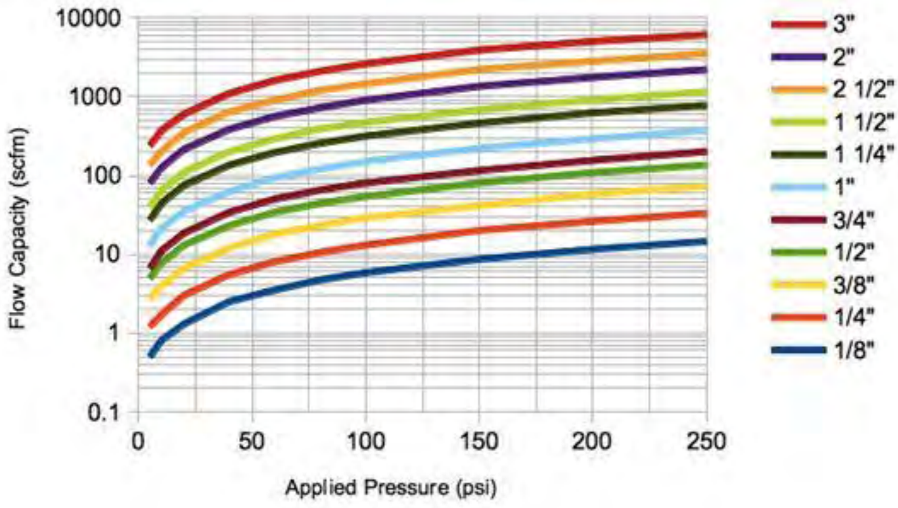


Figure 4.14: Air Volume vs. air pressure plot (The Engineering Toolbox)

4.3.9 Installation of LED light instead of T5 and T8 fluorescent tube light

LED tubes are a more popular in the factories. It is nothing more than a strip of LED assembled into a tube. LED is the greenest option available in all forms of lighting. And that is because it does not contain any mercury, which is harmful for environment unlike the fluorescent bulbs and lights. Fluorescent lights on the other hand contain mercury that is harmful for environment and their disposal is a concern. And this is a problem with both CFLs and fluorescent tube lights. The ballast is not used for the LED tubes so minor wiring will be required inside of the existing fixture and save the wattage consumed by ballast.

Fluorescent lights and many other conventional lights have a rated life, which is determined when half of the lights have failed. LED lights have a different method for determining life span. LED lamps do not burn out quickly as do conventional lamps. Rather, LEDs become gradually less bright over long periods of time. An LED has reached the end of its lifespan when only 70% of the original light output remains (30% lumen depreciation).The LED light life comparison with normal fluorescent light is given in figure 4.15.

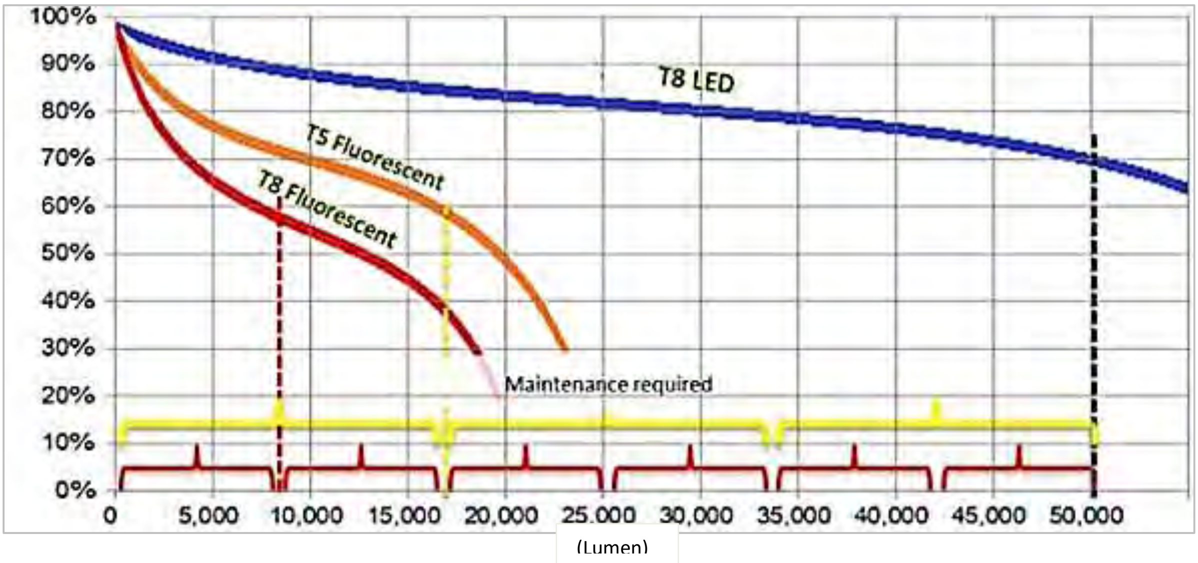


Figure 4.15: LED life comparison with Fluorescent Light

The picture of LED Light and Normal T8 and T5 Fluorescent Light are presented below (Figure 4.16)

Figure 4.16: T8, T5 and LED Tube Lights

LED tube light require low wattage while normal T5 or T8 florescent tube light require high wattage to produce the same lumen of light like LED. LED tube does not contain any ballast which is required for normal fluorescent tube light. Thus by replacing normal T5 and T8 fluorescent tube light at the production floor of garments industries with LED tube light, it is possible to save a significant amount of electrical energy with reducing the carbon emission.

4.3.10 Switching off unnecessary light during day time

During field visit it has been observed that there are many areas, where light intensity is much higher than the standard level of light requirements for production places. So the factory can be benefited by switching off some lights during day time where possible. Some advance devices like occupancy sensors may be installed to switch off lights. In this way the factory will be able to save energy and money as well. Saving electricity will reduce carbon emission which would occur for unnecessary electricity use.

4.3.11 Setting of servo motor instead of clutch motor in sewing machine

A servo motor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. Clutch motor of industrial sewing machine has a friction device which regulates the speed of rotation of the sheave. Frictional device provides a hard braking operation of the sewing machine after removing the foot from the pedal. The Servo Motor only runs when the operator's foot is on the pedal of sewing machine, in contrast to the constantly running clutch motors. This makes servo motors more energy efficient and quieter than a clutch motor. Servo motors are almost 65% to 80% energy saving compared to clutch motor. By replacing the clutch motors of sewing machines of garments industries, it is possible to reduce electricity consumption and thus reduce carbon emission related to electricity generation. The clutch motor and servo motor are presented in Figure 4.17:

Clutch Motor

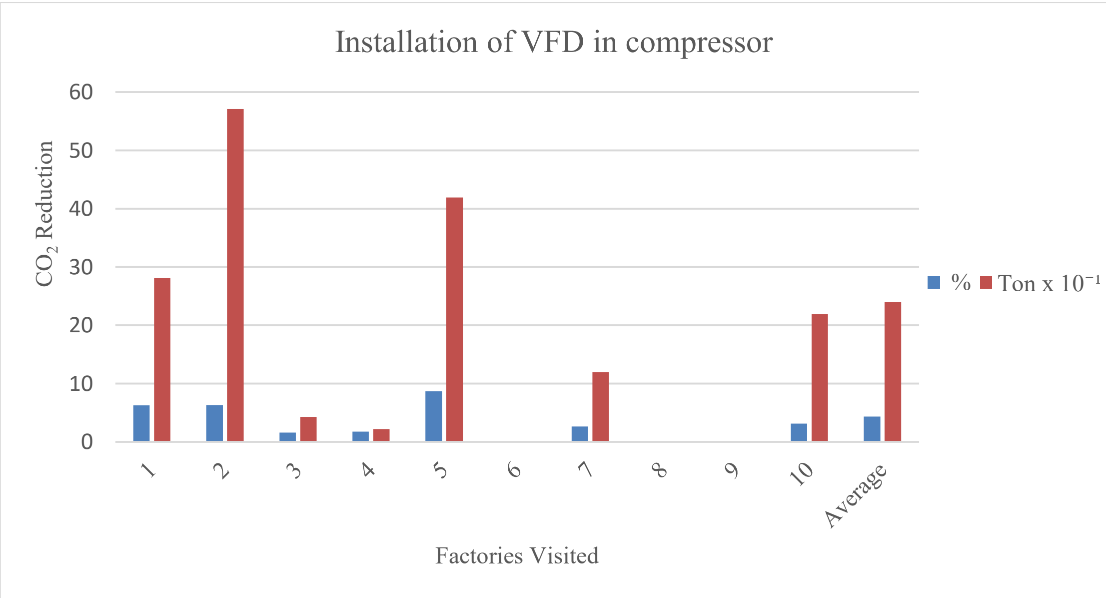
Servo Motor

Figure 4.17: Clutch and Servo Motor of Sewing Machine

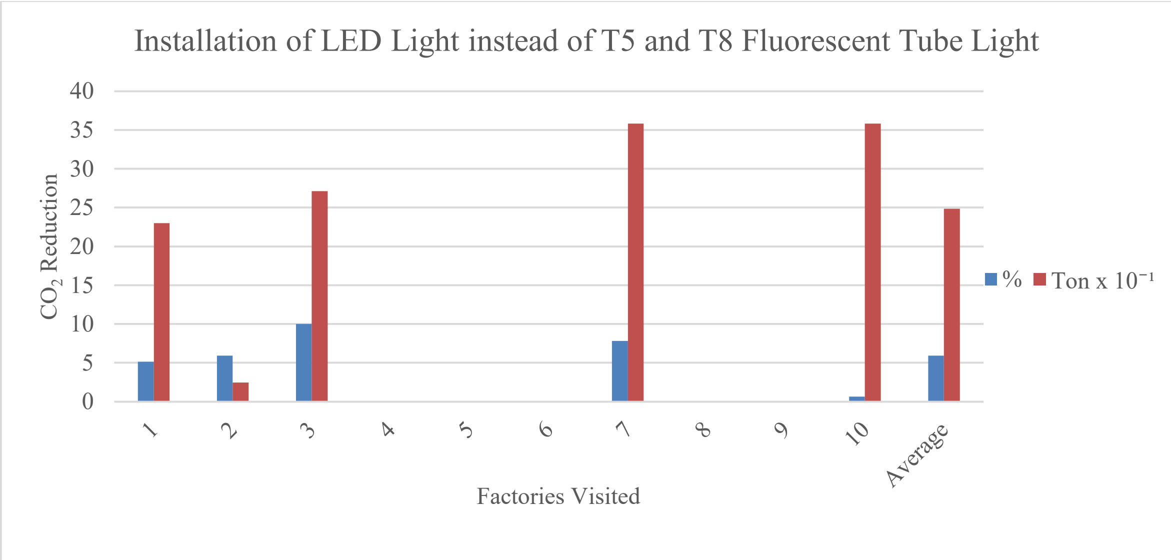
The CO_2 emission and energy consumption amount before and after adopting the above mentioned carbon reduction strategies at 10 garments industries are given in appendix A and B.

4.4 Carbon Emission Reduction Quantity by Adopting Several Strategies

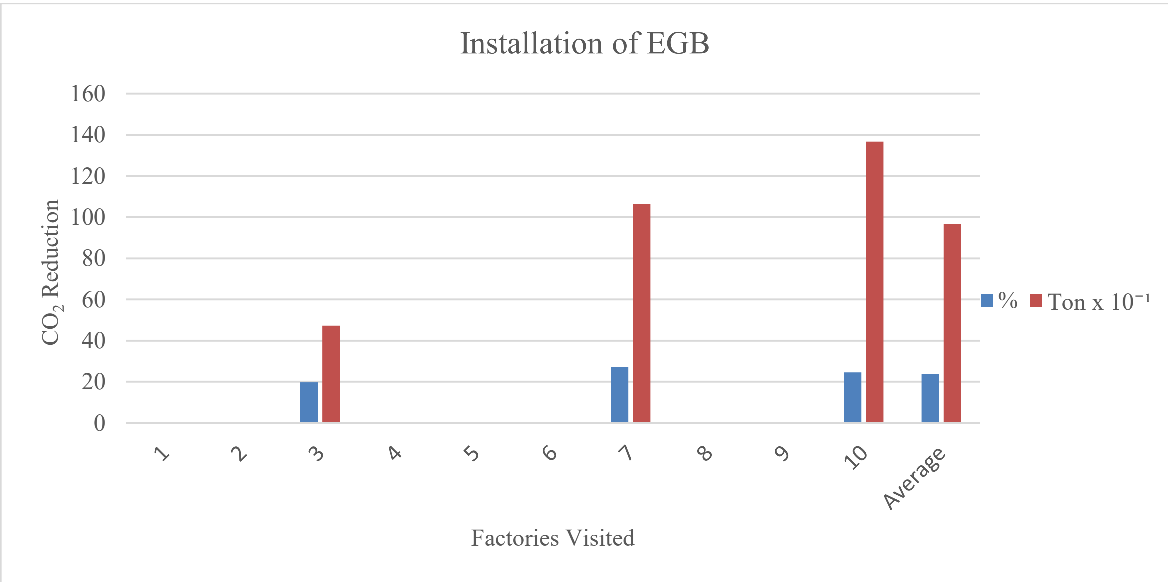
Several CO_2 emission reduction strategies could be applied to reduce the CO_2 emission from garments industries like installation of variable frequency drive (VFD) in compressor, installation of LED tube light instead of T5 and T8 fluorescent tube light, installation of EGB, installation of economizer in boiler, condensate recovery from boiler, auto blow down system in boiler, setting of servo motor in sewing machine, switching off unnecessary light during day time, repairing compressed air leakages, installation of G trap in steam iron, insulation of hot bare surfaces of steam distribution line. Possible carbon emission reduction amount (in Ton and percentage) by adopting these strategies at different garments industries is presented below (Figure 4.18)



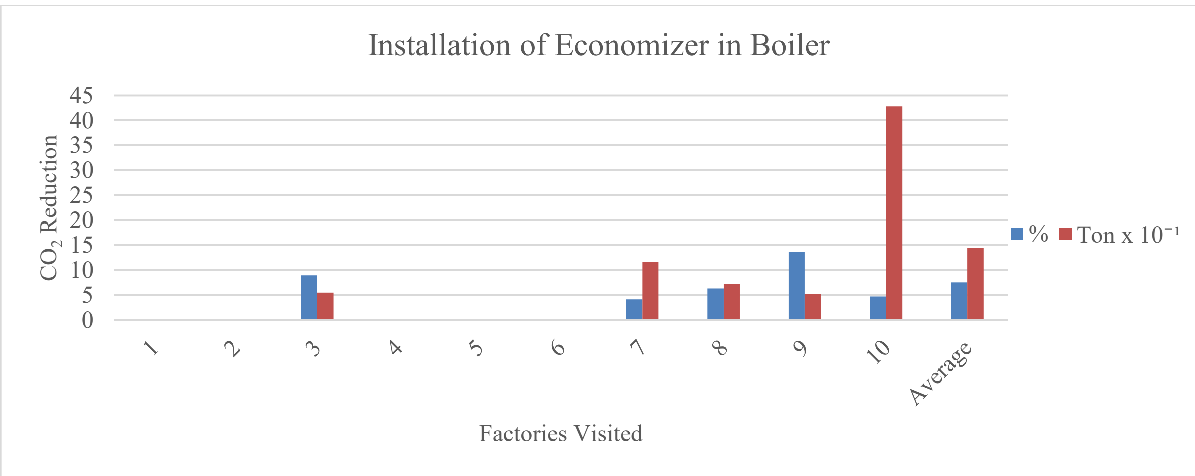
(a)


Installation of LED Light instead of T5 and T8 Fluorescent Tube Light
40
35
30
25
20
15
10
5
0
CO2 Reduction
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

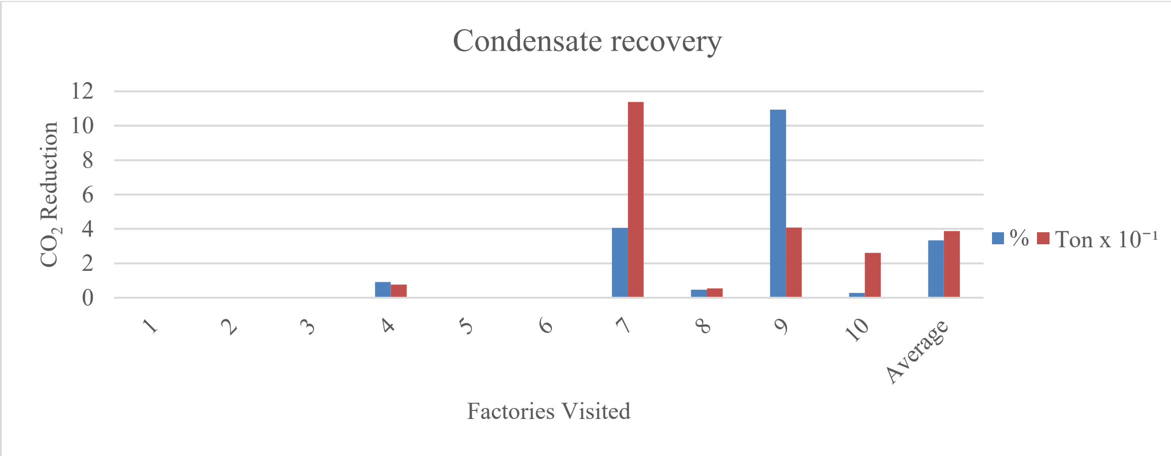
(b)


Installation of EGB
160
140
120
100
80
60
40
20
0
CO2 Reduction
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

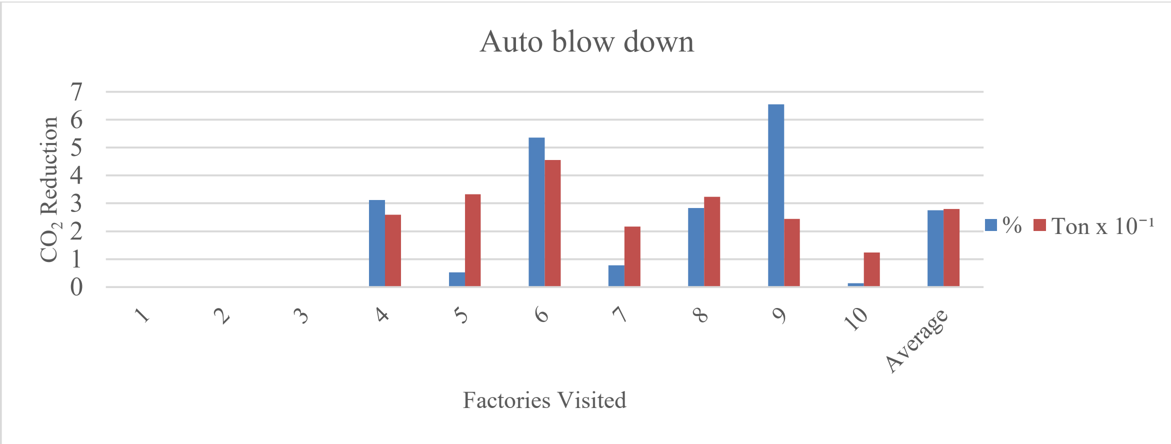
(c)


Installation of Economizer in Boiler
45
40
35
30
25
20
15
10
5
0
CO2 Reduction
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

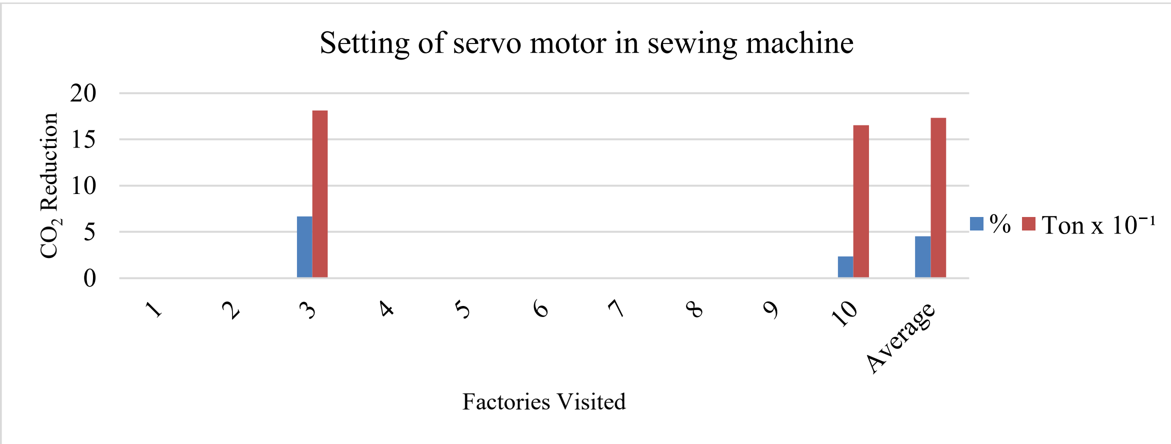
(d)


Condensate recovery
CO2 Reduction
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

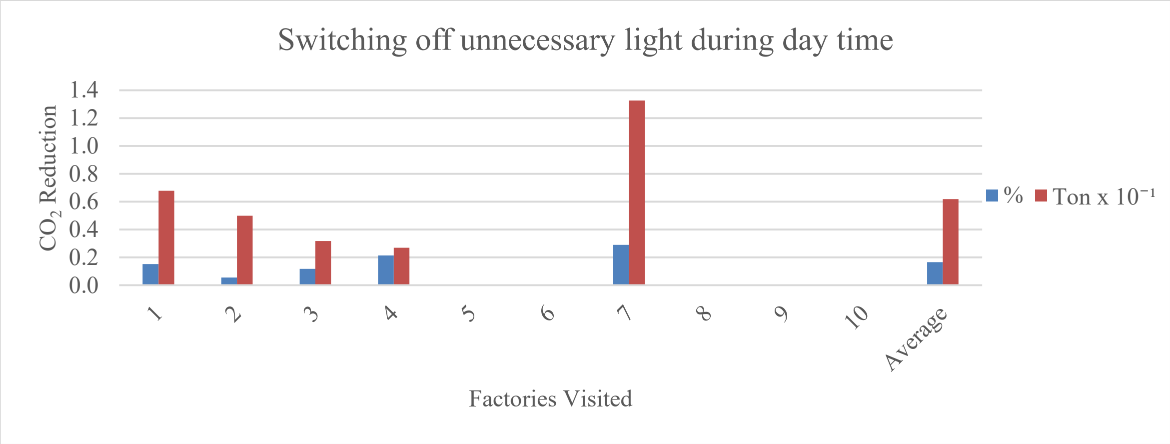
(e)


Auto blow down
CO2 Reduction
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

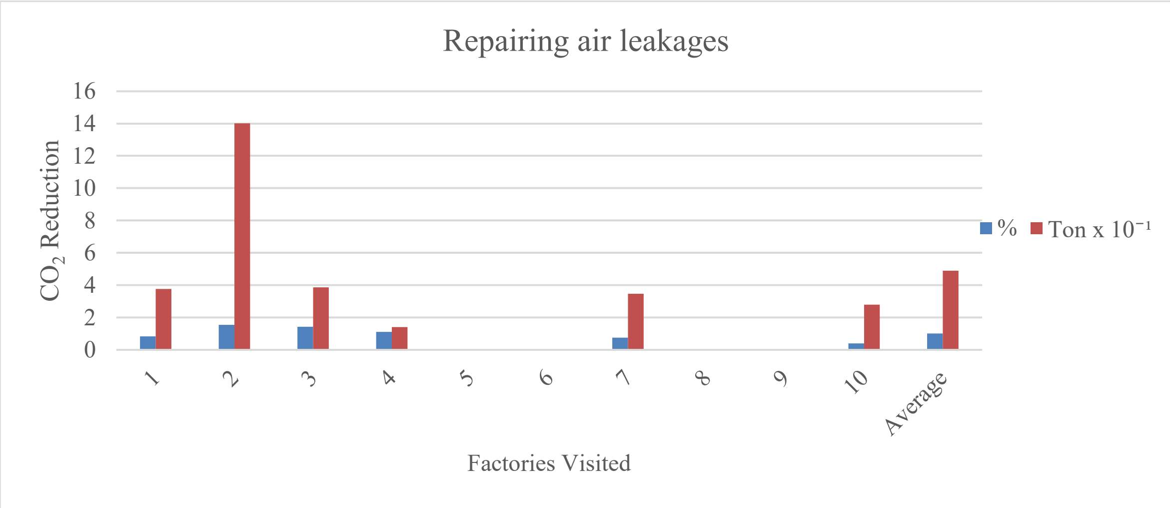
(f)


Setting of servo motor in sewing machine
CO2 Reduction
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

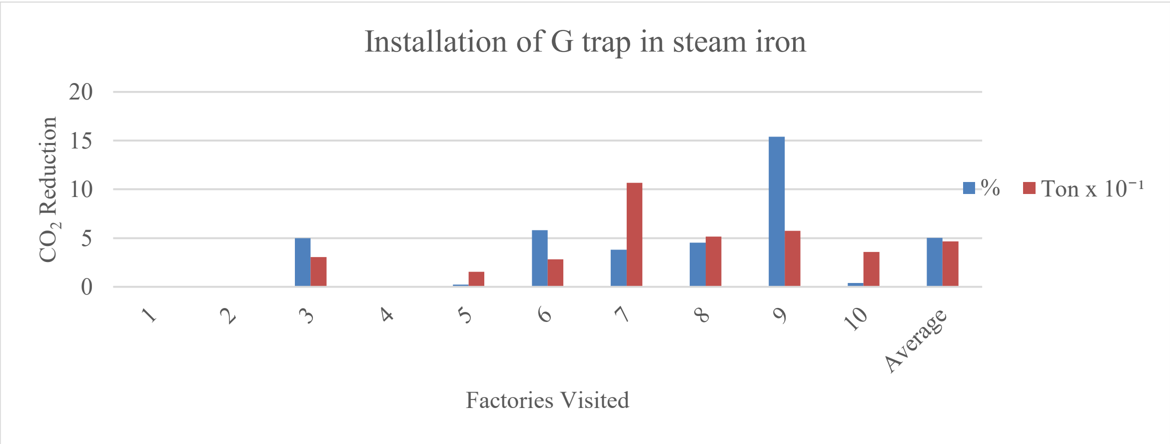
(g)


Switching off unnecessary light during day time
CO2 Reduction
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

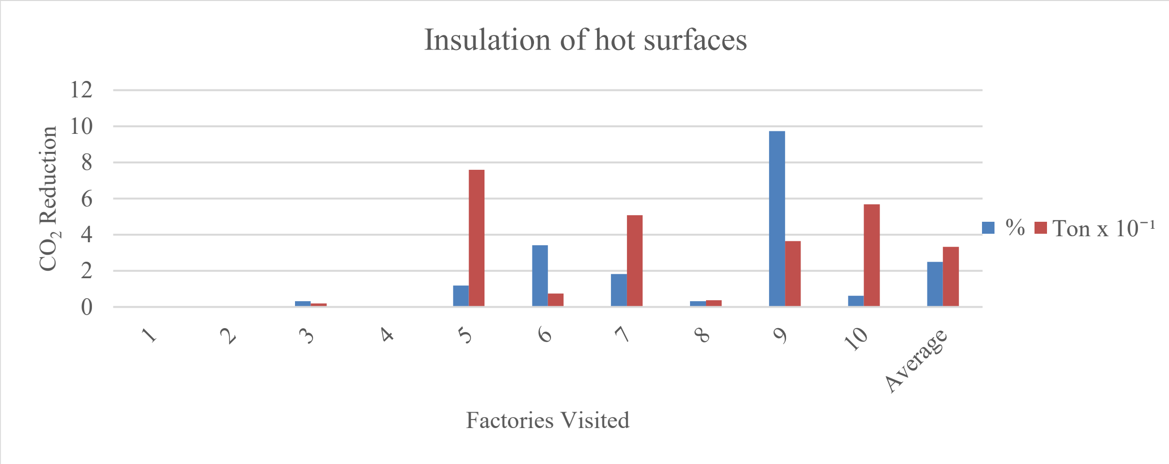
(h)


Repairing air leakages
CO2 Reduction
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

(i)


Installation of G trap in steam iron
CO2 Reduction
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
Average
Factories Visited
%
Ton x 10⁻¹

(j)



(k)

Figure 4.18: Possible Carbon Reduction at Different Garments Industries by Adopting Different Carbon Reduction Strategies – (a) Installation of VFD in compressor, (b) Installation of LED light instead of T5 and T8 fluorescent tube light, (c) Installation of EGB, (d) Installation of Economizer in Boiler, (e) Condensate recovery, (f) Auto blow down, (g) Setting of servo motor in sewing machine, (h) Switching off unnecessary light during day time, (i) Repairing air leakages, (j)Installation of G trap in steam iron, (k) Insulation of hot surfaces.

From the above Figure 4.18, it could be seen that all the carbon reduction measures are not applicable for all industries as some industry already have taken some measures and some industry use low capacity boiler due to their low production demand so in those cases some carbon reduction measures are also not applicable. For instance in case of Figure 4.18 (a) the recommendation of installing VFD in compressor is not required for 6^{th}, 8^{th} and 9^{th} no. factory, because VFD is already installed in their compressor. All other figures could be interpreted in similar way.

The average CO_2 reduction by adopting different carbon reduction strategies are presented altogether in figure 4.19:

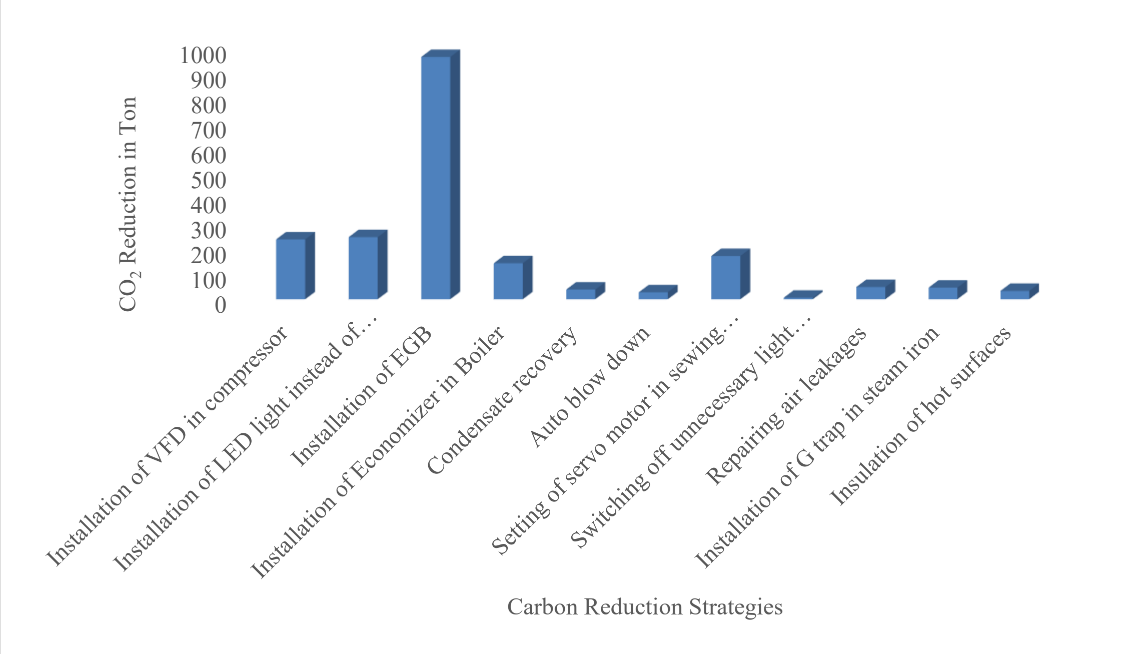


Figure 4.19: Average CO_2 Reduction by Adopting Different Carbon Reduction Strategies

From the above figure, it could be seen that among all carbon reduction strategies mentioned in this study, the installation of EGB shows maximum efficiency to reduce carbon emission by around 967 Ton annually. Besides this measure, installation of LED light instead of T5 and T8 fluorescent tube light, installation of VFD in compressor, replacing clutch motor with servo motor in sewing machines, the installation of economizer in boiler could reduce CO_2 emission by 248 Ton, 240 Ton, 173Ton and 144 Ton respectively. Other CO_2 reduction techniques also reduces CO_2 significantly except switching off unnecessary light during daytime whose carbon reduction percentage is very low comparing with other strategies. However as the payback period is immediate for this strategy and no cost is required for taking this measure thus it has not neglected and considered as a possible way for carbon emission reduction and improving energy efficiency.

4.5 Energy Saving Amount by Adopting Different Strategies

By adopting the carbon reduction strategies mentioned in chapter 3 of this report it is also possible to save energy. The average energy saving amount (in MJ and %) at readymade garments industries by adopting those strategies at garments industries is shown in Figure 4.20:

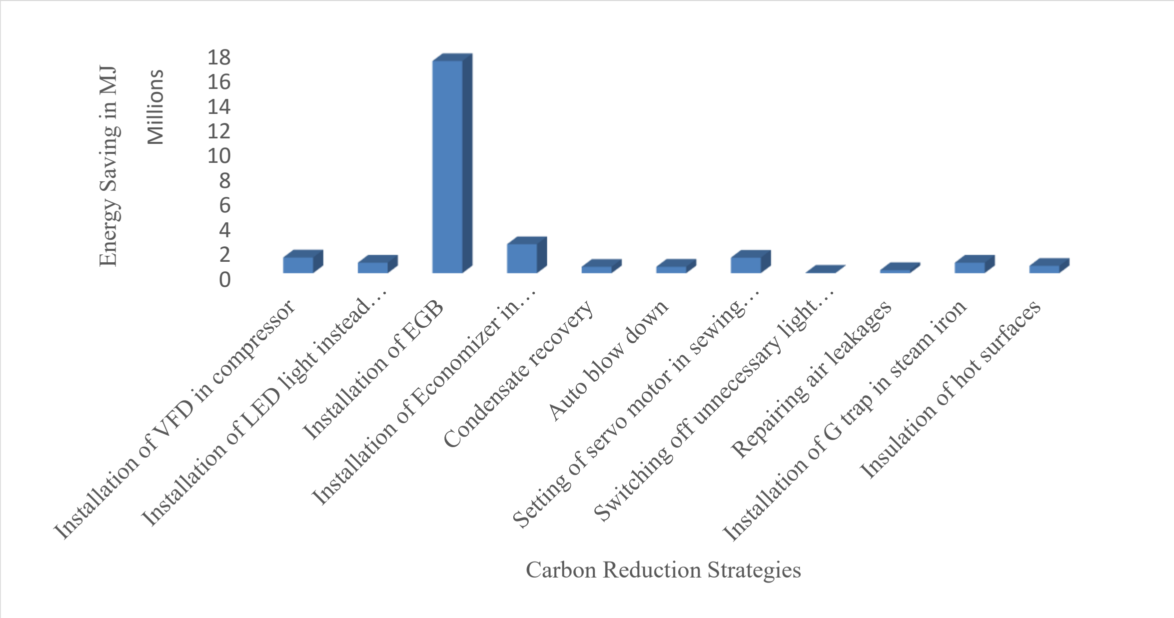


Figure 4.20: Average Energy Saving by Adopting Different Carbon Reduction Strategies

From the above figure, it could be seen that the installation of EGB could save maximum amount of energy i.e. 17117045MJ in comparison to other strategies and switching off light shows lowest possible energy saving i.e. 31832 MJ annually. However other strategies for carbon reduction are also beneficial to save energy.

4.6 Specific Carbon and Energy Reduction Benchmark

The production capacity of different garments industries varies from one another. The specific carbon reduction benchmark in kg/pc at garments industries by adopting different carbon reduction strategies has been estimated after analyzing all data collected from several garments industries. The specific carbon reduction benchmark at different garments industries is presented below (Figure 4.21):

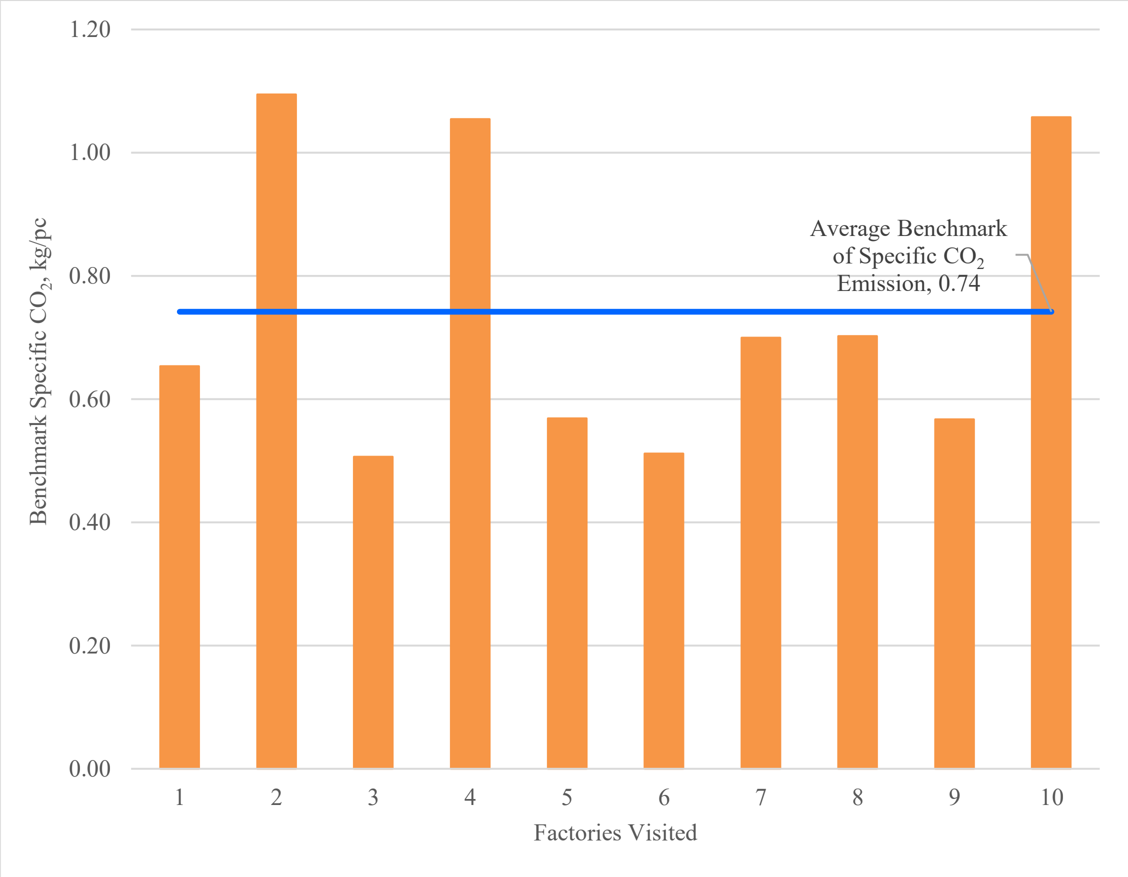


Figure 4.21: Specific Carbon Emission Benchmark at Different Garments Industries

From the above figure, it could be seen that by adopting different carbon reduction strategies the garments industries could reduce their carbon emission which ranges from 0.51 to 1.09 kg/pc and the average benchmark of specific carbon emission would be 0.74kg/pc.

Besides this CO_2 reduction it is also possible to reduce energy consumption at RMG sector by adopting these strategies. The average energy saving benchmark of garments industries are presented below (Figure 4.22):

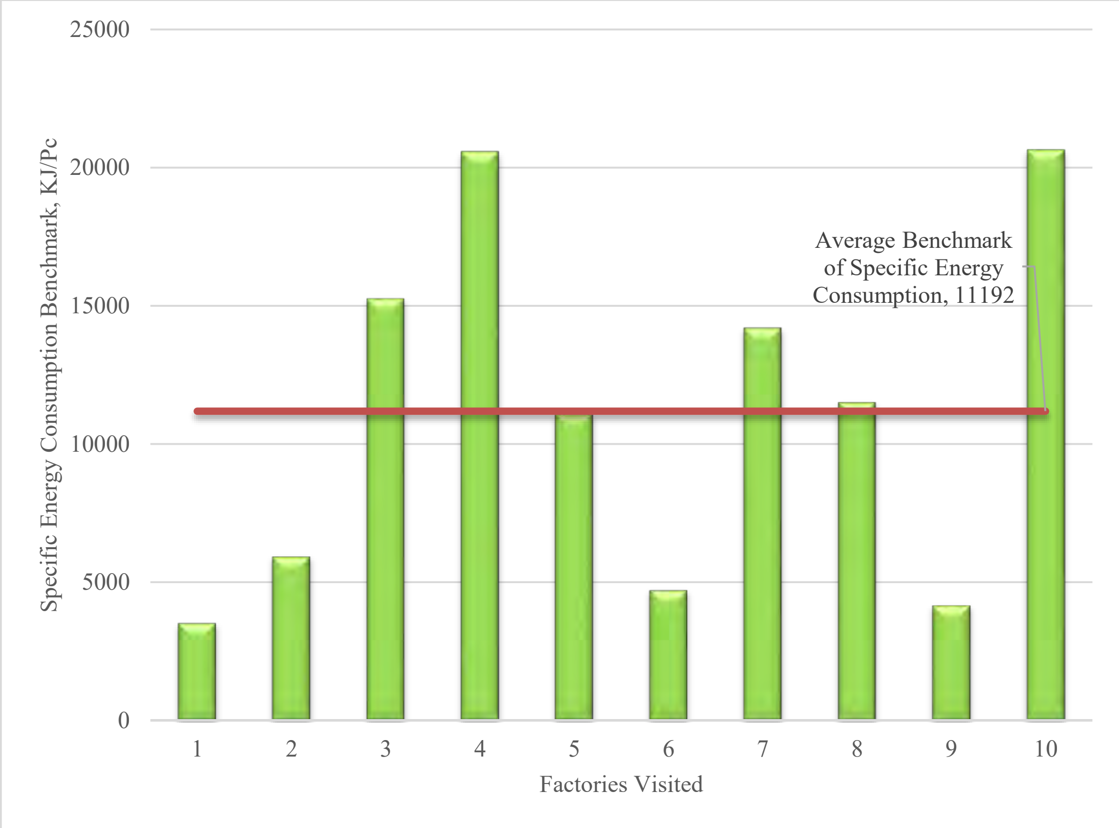


Figure 4.22: Energy Consumption Benchmark at Garments Industries

From the above Figure, it could be seen that the by adopting the carbon reduction strategies the garments industries could reduce their annual specific energy consumption about 11192 KJ/pc in average whereas the baseline of energy consumption has found 12752 KJ/pc. Thus the garments industries could save energy at about 12.61%.

4.7 Overall Estimation of Upper and Lower Limit of Carbon Reduction Potentials at Garments Industries

By analyzing the collected data from different garments industries it has been estimated that the upper limit of specific carbon reduction annually in garments industries is 1.21kg/pc and the lower limit of specific carbon reduction is 0.27 kg/pc at 95% confidence limit. However the average amount of specific CO_2 reduction is 0.74kg/pc. All these are presented in Figure 4.23:

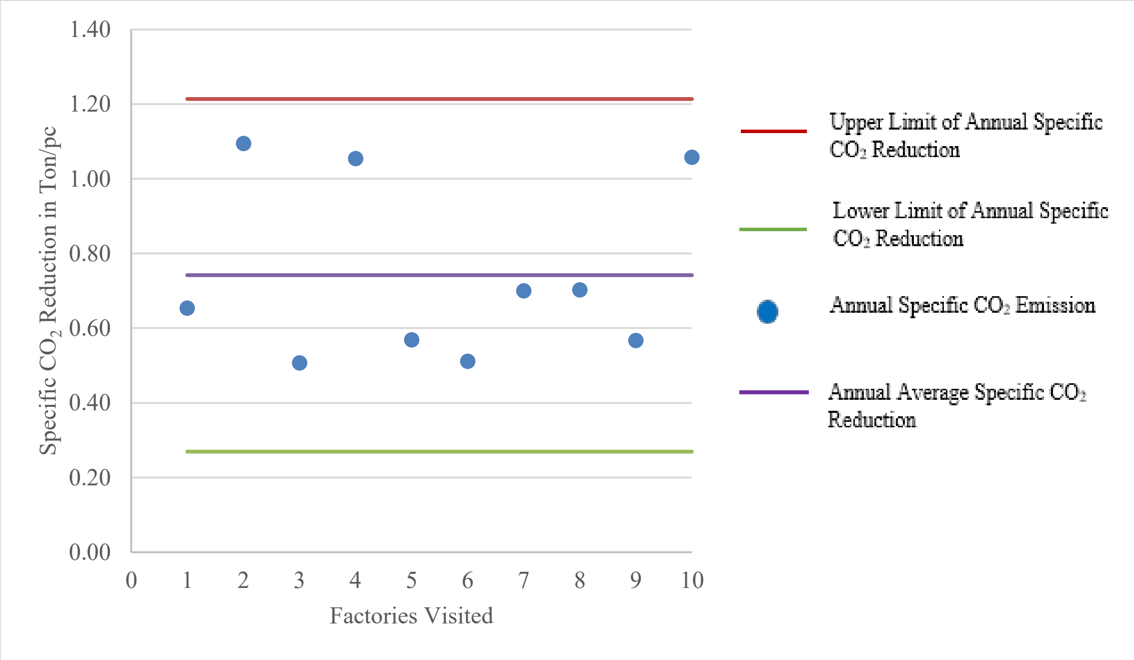


Figure 4.23: Upper and Lower Limit of Annual Specific CO_2 Reduction in Garments Industries (at 95% confidence level)

The annual specific CO_2 emission baseline and possible CO_2 reduction benchmark at garments industries are presented in Figure 4.24:

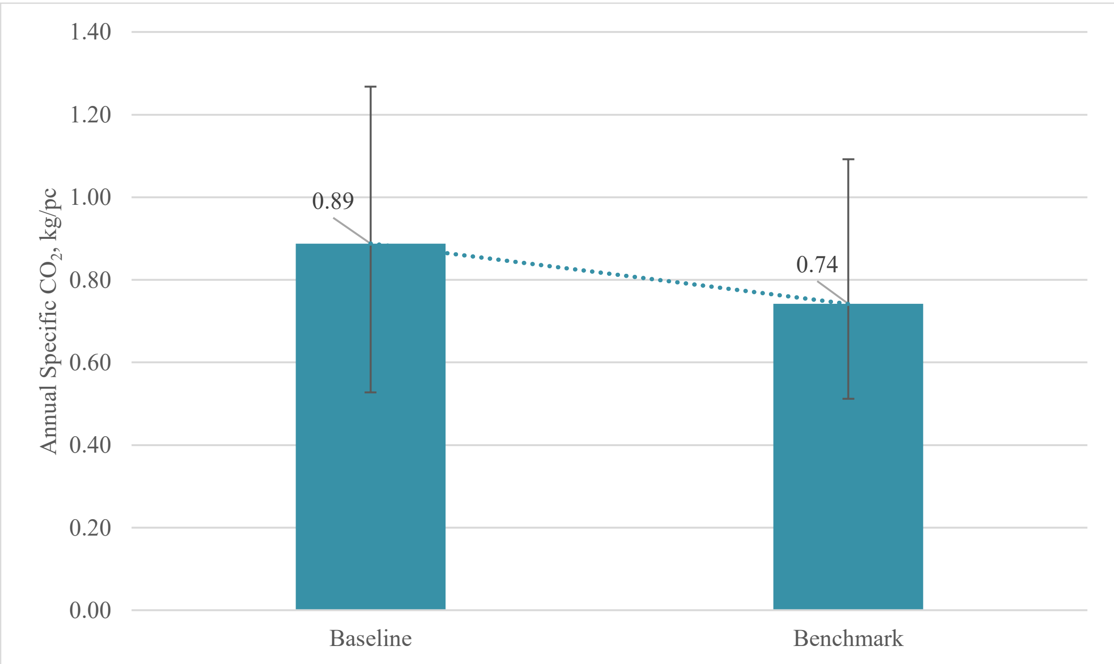


Figure 4.24: Annual Specific Carbon Emission and Carbon Reduction at Garments Industries

From the above figure which compares the existing carbon emission (baseline) and the emission after adopting the proposed carbon reducing strategies (benchmark) it has been found that the garments industries could reduce their annual specific carbon emission by 0.15kg/pc i.e. 15.26% of existing carbon emission after adopting the strategies.

4.8 Payback Period of Carbon Reduction Strategies

To implement different carbon reduction strategies suggested in this study, the industries need to invest money. After a certain time the industries could recover its initial outlay in terms of profits or savings. This is called payback period which is estimated for the visited garments industries. The payback period of carbon reduction strategies for garments industries are presented below (Figure 4.25):

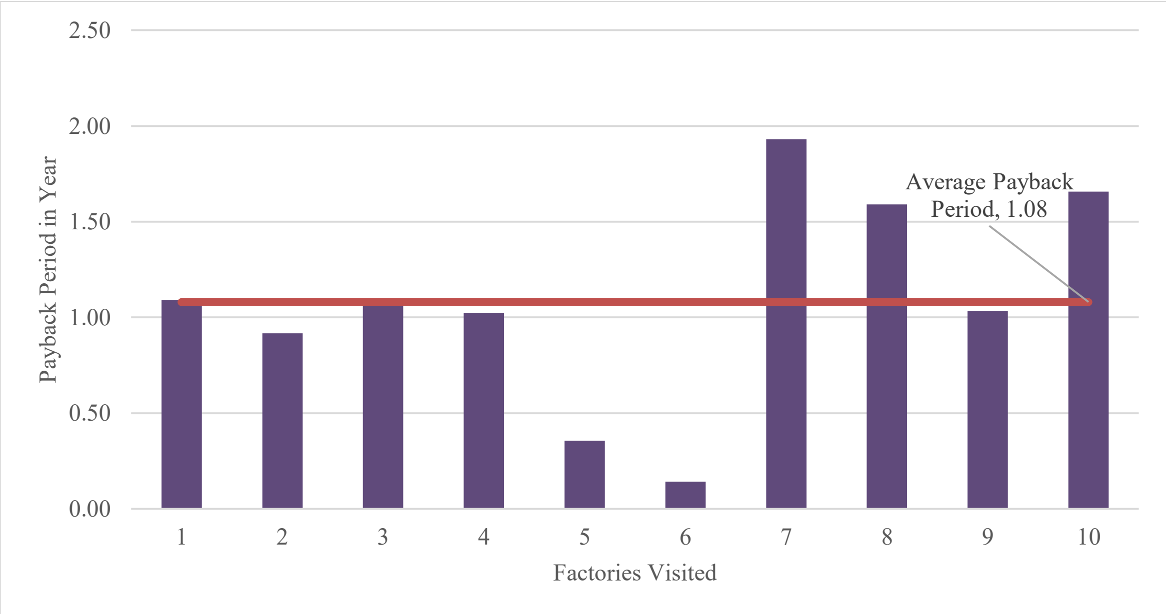


Figure 4.25: Payback Period of Carbon Reduction Strategies

From the above figure, it could be seen that there is a fluctuation in payback period of different garments industries. As some garments industries has already taken some carbon reduction and energy saving strategies thus their payback period is low as they need to invest low for adopt rest of the carbon reduction and energy saving strategies. The average payback period of carbon reduction and energy saving by adopting the carbon reduction strategies is 1.08 years.

4.9 Opportunities for Carbon Trading at Garments Sector in Bangladesh

The apparel industry is one of the biggest sources of producing greenhouse gasses (GHGs) on Earth, in many phase of the product life cycle from the raw materials, manufacturing and warehousing, transportation, consumer use, and disposal. The concept of carbon credits has come into existence as a result of increasing awareness of the need for controlling emissions. These credits are measured in units of Certified Emission Reductions (CERs). Carbon Credits have been given the recognition of an intangible commodity and can be traded on the commodities market Trading of carbon credits happens in the form of CERs or Certified Emissions Reductions. CERs are in the form of certificates, just like a stock. A CER is given by the CDM Executive Board to projects in developing countries to certify that they have reduced greenhouse gas emissions by one Ton of carbon dioxide per year. One CER is equivalent to one metric Ton of CO_2 or its equivalent.

According to "State and Trends of Carbon Pricing 2018" published by The World Bank Group and Ecofys, 45 national and 25 subnational jurisdictions are putting a price on carbon. Carbon prices vary substantially, from less than US \$1/tCO_2e to a maximum of US \$139/tCO_2e (chart given in appendix I). Most initiatives saw an increase in their 2018 price levels compared to those in 2017. One substantial change was the growth in the European Union Allowance (EUA) price from € 5/tCO_2e to €13/tCO_2e (US \$7/tCO_2e to US \$16/tCO_2e) as more certainty developed on the future of the European Union (EU) ETS in the post-2020 period (World Bank and Ecofys, 2018). The carbon pricing at garments industries in Bangladesh has been estimated based on EU ETS. The carbon credit and carbon trading value at different garments industries is presented in Table 4.1:

Table 4.1 Carbon Credit and Carbon Trading Value at Different Garments Industries

No. of Visited Factories	Carbon Credit (CER)/year	Carbon Trading Value US $/year
1.	555.46	8887.32
2.	1252.03	20032.47
3.	1654.45	26471.24
4.	72.66	1162.57
5.	544.32	8709.19
6.	81.14	1298.28
7.	1998.28	31972.51
8.	164.83	2637.23
9.	210.12	3361.99
10.	2383.14	38130.28

By analyzing the carbon reduction possibilities of the visited factories it has been estimated that individual garments industry could achieve a carbon credit ranges around 81 CER/year to 2383 CER/year based on their carbon reduction performance. By trading the carbon credit the individual industry could earn money which ranges around US$ 1163/year to US$ 38130/year. A company has two ways to reduce emissions. One, it can reduce the GHG (greenhouse gases) by adopting new technology or improving upon the existing technology to attain the new norms for emission of gases. Or it can tie up with developing nations and help them set up new technology that is eco-friendly, thereby helping developing country or its companies "earn credits. In this study the first way of carbon reduction has been presented for ready-made garments industries. The RMG industry is the largest export earning industrial sector in Bangladesh and the manufacturing process of garments is associated with energy consumption and carbon emission. In economic sense the carbon trading could help the industries to get more international buyers and could provide a scope for earning more foreign currency by exporting low carbon emitting products. Moreover in case of achieving environmental sustainability the carbon trading helps to reduce carbon emission and thus contributes for reducing global warming.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Day by day global climate is changing due to increasing Greenhouse Gas (GHG) emission. The quantity of GHG is expressed as Carbon Dioxide Equivalent i.e. CO_2e. The carbon emission (CO_2e) from manufacturing industries play a vital role for increasing surface temperature which ultimately causes global warming. In this study direct CO_2 emission from onsite fuel combustion and indirect emission from purchased electricity at different garments industries has been monitored. In garments industry the major source of CO_2 emission is fuel combustion in generator and boiler. As steam is required for finishing activities of garments, so direct fuel combustion is occurred in boiler which emits CO_2. Beside this electricity is also used in garments industry for operating cutting and sewing machines as well as for lighting purpose in whole factory. Electricity generates in generator and also purchased from national grid which is another source of CO_2 emission. The following conclusions may be drawn within the limited scope of this study.

I. Based on the result of this study it has been found that the garments industries emits about 0.89 kg/pc specific CO_2 which is the baseline average CO_2 emission due to consuming specific energy of about 12752 KJ/pc.

II. Based on the data collected from different garments industries it has been estimated that the maximum possible amount of annual specific carbon reduction in garments industries is 1.21kg/pc and minimum amount of specific carbon reduction is 0.27 kg/pc. After adopting different carbon reduction strategies the garments industries could reduce their existing carbon emission by 15.26% and the benchmark of specific CO_2 emission would be about 0.74 kg/pc.

III. The garments industries could reduce their existing carbon emission by adopting different carbon reduction strategies such as- Installation of VFD in compressor, Installation of LED light instead of T5 and T8 fluorescent tube light, Installation of EGB, Installation of Economizer in Boiler, Condensate recovery, Auto blow down, Setting of servo motor in sewing machine, Switching off unnecessary light during day time, Repairing air leakages, Installation of G trap in steam iron, Insulation of hot surfaces. Among all carbon reduction strategies the highest carbon reduction is possible by installing Exhaust Gas Boiler (EGB) which could reduce CO_2 in average 967 Ton and save energy around 17117045 MJ annually. In contrast, switching off unnecessary light during daytime shows lowest amount of carbon reduction and energy saving which are 6 Ton and 31832 MJ respectively. However as the payback period is immediate for this strategy and no cost is required for taking this measure thus it has considered as a possible way for carbon emission reduction and improving energy efficiency.

IV. The garments industries could reduce the current specific energy consumption by 12.61% by adopting the carbon reduction strategies and the benchmark of specific energy consumption would be11192 KJ/pc in average.

V. By adopting the carbon reduction strategies, the garments industries could save their energy cost and the average payback period of these carbon reduction strategies is 1.08 years.

Besides, there is an opportunities in RMG sector for carbon trading by reducing carbon emission and saving energy through the implementation of different carbon reducing strategies.

To recapitulate it could be said that reduction of carbon emission from garments manufacturing industries will help to reduce national CO_2 emission of Bangladesh and it will ultimately reduce global warming.

5.2 Recommendations for Future Work

In this study, carbon emission from stationary combustion sources and purchased electricity i.e. direct and indirect emission sources have been considered. The carbon emission from corporate value chain as well as emission from transport used in the garments industries has not considered here. So for future work, it is recommended to consider emission from transport used in industrial activities. As well as emission from corporate value chain could be considered if proper data is available. Moreover the result could be analyzed using regression model if more factories' data could be acquired.

Carbon emission and reduction scope from garments waste has not been covered in this study. Thus estimating the CO_2 emission from garments wastage is recommended for the future works.

Moreover an in depth study and feasibility analysis for carbon trading at Garments industries could be taken into consideration in future work.

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APPENDIX-A

Carbon Emission Reduction Before and After Adopting Carbon Reduction Strategies at Garments industries

No. of Visited Factories	Total CO_2 Emission (Ton)	CO_2 Emission after adopting Carbon Reduction Strategies (Ton)	Baseline of Specific CO_2 Emission (kg/pc)	Benchmark of Specific CO_2 Emission (kg/pc)
1.	4481.48	3926.02	0.75	0.65
2.	9025.51	7773.48	1.27	1.09
3.	3322.42	1667.96	1.01	0.51
4.	1263.61	1190.95	1.12	1.05
5.	11192.30	10647.97	0.60	0.57
6.	2776.60	2695.45	0.53	0.51
7.	8090.67	6092.39	0.93	0.70
8.	1494.65	1329.83	0.79	0.70
9.	1819.59	1609.46	0.64	0.57
10.	16664.37	14281.23	1.23	1.06

APPENDIX-B

Energy Consumption Reduction Before and After Adopting Carbon Reduction Strategies at Garments industries

No. of Visited Factories	Total Energy Consumption (MJ)	Energy Consumption after adopting Carbon Reduction Strategies (MJ)	Baseline of Specific Energy Consumption (KJ/pc)	Benchmark of Specific Energy Consumption (KJ/pc)
1.	24403306.76	21425866.61	4082.54	3564.63
2.	49225563.02	42518055.72	6939.07	5986.02
3.	63404745.97	50361890.49	19266.39	15282.55
4.	23715357.55	22842906.10	21367.17	20581.10
5.	212381985.57	208193462.54	11345.19	11121.45
6.	27361123.07	25001698.53	5224.34	4769.28
7.	151485229.41	124094081.05	17338.79	14228.59
8.	24899578.09	21739782.23	13273.96	11538.75
9.	15295408.96	11912732.08	5429.88	4214.58
10.	313884695.71	278604564.15	23251.97	20630.02

APPENDIX-C

Carbon Emission Reduction Percentage of Individual Factories After adopting Carbon Reduction Strategies:

Carbon Reduction Strategies	Carbon Reduction Percentage (%) of Individual Factories										Average Reduction %
	1	2	3	4	5	6	7	8	9	10	
A. Installation of VFD in compressor	6.27	6.33	1.59	1.76	8.68	-	3.00	-	-	3.08	4.33
B. Installation of LED light instead of T5 and T8 fluorescent tube light	5.13	5.93	10.00	-	-	-	7.82	-	-	0.65	5.91
C. Installation of effluent gas boiler (EGB)	-	-	19.76	-	-	-	27.19	-	-	24.61	23.86
D. Installation of Economizer in Boiler	-	-	8.94	-	-	-	4.13	6.27	13.62	4.65	7.52
E. Condensate recovery System	-	-	-	0.92	-	-	4.06	0.48	10.93	0.28	3.34
F. Auto blowdown	-	-	-	3.12	0.52	5.36	0.77	2.84	6.55	0.13	2.76
G. Setting of servo motor instead of clutch motor in sewing machine	-	-	2.72	-	-	-	-	-	-	2.35	2.54
H. Switching off unnecessary light during day time	0.15	0.06	0.12	0.21	-	-	0.29	-	-	-	0.17
I. Repairing air leakages	0.84	1.55	1.42	1.11	-	-	0.76	-	-	0.40	1.01
J. Installation of G trap in steam iron	-	-	4.99	-	0.24	5.81	3.81	4.52	15.38	0.39	5.02
K. Insulation of hot surfaces	-	-	0.32	-	1.20	3.42	1.82	0.32	9.73	0.62	2.49

Note: This sign "-" indicates that the strategy is not applicable for the individual factories.

APPENDIX-D

Energy Saving Percentage of Individual Factories After adopting Carbon Reduction Strategies:

Carbon Reduction Strategies	Energy Saving Percentage (%) of Individual Factories										Average Saving %
	1	2	3	4	5	6	7	8	9	10	
A. Installation of VFD in compressor	6.17	6.22	0.17	0.46	2.26	-	3	-	-	3.08	3.00
B. Installation of LED light instead of T5 and T8 fluorescent tube light	5.05	5.83	1.08	-	-	-	7.83	-	-	0.65	4.09
C. Installation of effluent gas boiler (EGB)	-	-	19.78	-	-	-	23.26	-	-	12.02	18.36
D. Installation of Economizer in Boiler	-	-	6.31	-	-	-	3.26	6.54	10.36	3.68	6.03
E. Condensate recovery System	-	-	-	0.92	-	-	2.34	0.36	8.32	0.21	2.43
F. Auto blowdown	-	-	-	3.12	0.56	5.36	0.77	2.84	6.56	0.13	2.76
G. Setting of servo motor instead of clutch motor in sewing machine	-	-	2.94	-	-	-	-	-	-	2.36	2.65
H. Switching off unnecessary light during day time	0.15	0.05	0.01	0.06	-	-	0.29	-	-	-	0.11
I. Repairing air leakages	0.83	1.53	0.15	0.29	-	-	0.76	-	-	0.40	0.66
J. Installation of G trap in steam iron	-	-	4.03	-	0.23	5.81	2.95	3.76	12.32	0.34	4.20
K. Insulation of hot surfaces	-	-	0.24	-	0.96	3.42	1.44	0.24	7.40	0.49	2.03

APPENDIX-E

Payback Period of Carbon Reduction Strategies:

Carbon Reduction Strategies	Number of Visited Factories										Average Payback Period, months
	1	2	3	4	5	6	7	8	9	10	
A. Installation of VFD in compressor	14.30	10.54	13.42	8.21	3.58	-	28.47	-	-	24.29	14.7
B. Installation of LED light instead of T5 and T8 fluorescent tube light	14.03	14.29	6.41	-	-	-	20.99	-	-	11.71	13.5
C. Installation of effluent gas boiler (EGB)	-	-	2.52	-	-	-	30.14	-	-	23.45	18.7
D. Installation of Economizer in Boiler	-	-	19.09	-	-	-	11.57	20.52	20.23	2.80	14.8
E. Condensate recovery System	-	-	-	29.51	-	-	12.57	61.42	8.24	42.56	30.9
F. Auto blowdown	-	-	-	25.90	30.45	2.17	44.12	18.17	24.05	59.63	29.2
G. Setting of servo motor instead of clutch motor in sewing machine	-	-	19.21	-	-	-	-	-	-	29.75	24.5
H. Switching off unnecessary light during day time	Immediate	Immediate	Immediate	Immediate	-	-	Immediate	-	-	-	Immediate
I. Repairing air leakages	0.64	0.68	0.35	0.43	-	-	0.84	-	-	0.80	0.6
J. Installation of G trap in steam iron	-	-	28.11	-	7.55	1.50	14.93	13.68	11.13	13.97	13.0
K. Insulation of hot surfaces	-	-	16.15	-	2.01	1.38	2.98	5.10	2.31	2.59	4.6

APPENDIX-F

Stack Air Emission Test Data of Individual Factories

No. of Visited Factories	Name of Stationary Combustion Sources	CO mg/m^3	CO_2 %	NO mg/m^3	NOx mg/m^3	SO_2 mg/m^3	O_2 %	Excess Air %	Flue Temperature °C
1	Diesel Generator- G 01	166	7.7	2468	2591.1	0	10.6	102.9	401
	Diesel Generator- G 02	880	8.3	1594	1673.6	0	9.8	90	467
	Diesel Generator- G 03	245	8.3	2710	2845.7	0	10.0	91.7	415
	Diesel Generator- G 04	257	2.6	373	391.9	0	17.3	497.1	144
2	Diesel Generator- G 01	868	9.1	1318	1383.4	0	9.0	75.6	305
	Diesel Generator- G 02	222	7.9	1248	1309.9	0	10.5	101.0	302
	Diesel Generator- G 03	756	8.1	1035	1086.3	0	10.1	93.5	283
	Diesel Generator- G 04	456	7.6	1062	1114.9	0	11.0	111.1	300
	Diesel Generator- G 05	616	7.6	1146	1203.7	0	10.9	109.0	363
	Diesel Generator- G 06	309	8.2	1037	1089	0	9.2	78.6	408
3	Natural Gas Boiler- B 01	27	8.2	54	56.7	2	10.1	93.5	326
	Diesel Boiler- B 02	6	10.7	100	105	0	6.8	48.2	290
	Gas Generator-G 01	1278	10.4	2300	2415.4	0	7	50.4	502
	Diesel Generator- G 02	100	7.3	1882	1976.1	0	11.6	124.7	350
	Diesel Generator- G 03	252	7.3	1409	1479.6	0	11.0	111.1	361
	Diesel Generator- G 04	154	8.6	875	918.9	0	10.3	97.2	292
4	Boiler- B 01	947	7.1	171	179.3	52	8.5	68.5	121
	Gas Generator-G 01	936	7.1	498	523.3	64	8.3	67.2	557
	Diesel Generator- G 02	141	5.6	1421	1493.1	0	13.4	175	278

No. of Visited Factories	Name of Stationary Combustion Sources	CO mg/m^3	CO_2 %	NO mg/m^3	NOx mg/m^3	SO_2 mg/m^3	O_2 %	Excess Air %	Flue Temperature °C
5	Duel Fuel Boiler-B-01	3	9.4	61	64.1	2	8.5	68.5	190
	Natural Gas Boiler- B 02	5.2	10.1	69	72.5	5	3.2	17.4	209
	Diesel Boiler-B 03	0	11.3	75	78.8	2	6.4	39.3	170
	Gas Generator- G 01	83.2	2.1	62	65.1	0	10.2	64.3	78
	Diesel Generator-G 02	315	9.6	190	198.8	31	8.5	68.5	133
	Diesel Generator-G 03	435.2	9.2	579	609	22.5	8.8	69.9	522
	Diesel Generator-G 04	100	9.9	1085	1149.2	0	7.72	57.1	360
6	Natural Gas Boiler-B 01	33	9.1	54	56	2	5.1	31.7	292
	Diesel Boiler-B 02	8	11.1	79	83	2	6.2	41.9	232
7	Natural Gas Boiler-B 01	7477.1	11.9	71.7	75.25	649.3	0	0.0	216
	Gas Generator- G 01	674.5	7.2	906.8	952.2	0	8.4	66.7	546
	Gas Generator- G 02	714.8	7.7	2999	3148.8	0.0	7.5	55.6	577
8	Natural Gas Boiler-B 01	11456	10.9	21	22.05	8963	1.9	10.0	368
	Natural Gas Boiler-B 02	5605	10.9	104	109.0	229	1.7	8.8	232

No. of Visited Factories	Name of Stationary Combustion Sources	CO mg/m^3	CO_2 %	NO mg/m^3	NOx mg/m^3	SO_2 mg/m^3	O_2 %	Excess Air %	Flue Temperature °C
09	Natural Gas Boiler-B 01	16	9.8	45	47	0	3.7	21.5	287
10	Natural Gas Boiler-B 01	>11456	11.7	53.5	56.2	654.2	0.3	1.4	227
	Gas Generator- G 01	292.0	6.9	323	339.3	95.3	8.9	73.6	478
	Gas Generator- G 02	446.2	6.9	434.8	456.6	97.5	8.9	73.1	477

APPENDIX-G

Boiler's Feed water and Blowdown Water Test Data of Individual Factories

No. of Visited Factories	Name of Unit	Feed water TDS mg/l	Feed Water Hardness mg/l	Blowdown Water TDS Test Result mg/l	Blowdown Water Total Hardness Test (as $CaCO_3$) Result mg/l
1	No Boiler	Not Applicable	Not Applicable	Not Applicable	Not Applicable
2	No Boiler	Not Applicable	Not Applicable	Not Applicable	Not Applicable
3	Natural Gas Boiler- B 01	84.2	60	138.9	48
	Diesel Boiler- B 02	84.2	60	680	108
4	Boiler- B 01	272	188	2016	16
5	Diesel Boiler- B 03	300	4	2604	4
6	Diesel Boiler- B 02	72	16	200	56
7	Natural Gas Boiler-B 01	308	4	4506	4
8	Natural Gas Boiler-B 01	160	8	1928	184
	Natural Gas Boiler-B 02	160	8	2464	208
9	Natural Gas Boiler- B 01	304	4	2960	08
10	Natural Gas Boiler- B 01	204	76	3460	16

APPENDIX-H

Net Calorific Value of Fuel from IPCC 2006 Guideline

TABLE 1.2
DEFAULT NET CALORIFIC VALUES (NCVS) AND LOWER AND UPPER LIMITS OF THE 95% CONFIDENCE INTERVALS [1]

Fuel type English description		Net calorific value (TJ/Gg)	Lower	Upper
Crude Oil		42.3	40.1	44.8
Orimulsion		27.5	27.5	28.3
Natural Gas Liquids		44.2	40.9	46.9
Gasoline	Motor Gasoline	44.3	42.5	44.8
	Aviation Gasoline	44.3	42.5	44.8
	Jet Gasoline	44.3	42.5	44.8
Jet Kerosene		44.1	42.0	45.0
Other Kerosene		43.8	42.4	45.2
Shale Oil		38.1	32.1	45.2
Gas/Diesel Oil		43.0	41.4	43.3
Residual Fuel Oil		40.4	39.8	41.7
Liquefied Petroleum Gases		47.3	44.8	52.2
Ethane		46.4	44.9	48.8
Naphtha		44.5	41.8	46.5
Bitumen		40.2	33.5	41.2
Lubricants		40.2	33.5	42.3
Petroleum Coke		32.5	29.7	41.9
Refinery Feedstocks		43.0	36.3	46.4
Other Oil	Refinery Gas [2]	49.5	47.5	50.6
	Paraffin Waxes	40.2	33.7	48.2
	White Spirit and SBP	40.2	33.7	48.2
	Other Petroleum Products	40.2	33.7	48.2
Anthracite		26.7	21.6	32.2
Coking Coal		28.2	24.0	31.0
Other Bituminous Coal		25.8	19.9	30.5
Sub-Bituminous Coal		18.9	11.5	26.0
Lignite		11.9	5.50	21.6
Oil Shale and Tar Sands		8.9	7.1	11.1
Brown Coal Briquettes		20.7	15.1	32.0
Patent Fuel		20.7	15.1	32.0
Coke	Coke Oven Coke and Lignite Coke	28.2	25.1	30.2
	Gas Coke	28.2	25.1	30.2
Coal Tar [3]		28.0	14.1	55.0
Derived Gases	Gas Works Gas [4]	38.7	19.6	77.0
	Coke Oven Gas [5]	38.7	19.6	77.0
	Blast Furnace Gas [6]	2.47	1.20	5.00
	Oxygen Steel Furnace Gas [7]	7.06	3.80	15.0
Natural Gas		48.0	46.5	50.4
Municipal Wastes (non-biomass fraction)		10	7	18
Industrial Wastes		NA	NA	NA
Waste Oil [8]		40.2	20.3	80.0
Peat		9.76	7.80	12.5

TABLE 1.2 (CONTINUED) DEFAULT NET CALORIFIC VALUES (NCVS) AND LOWER AND UPPER LIMITS OF THE 95% CONFIDENCE INTERVALS [1]				
Fuel type English description		**Net calorific value (TJ/Gg)**	**Lower**	**Upper**
Solid Biofuels	Wood/Wood Waste [9]	15.6	7.90	31.0
	Sulphite lyes (black liquor) [10]	11.8	5.90	23.0
	Other Primary Solid Biomass [11]	11.6	5.90	23.0
	Charcoal [12]	29.5	14.9	58.0
Liquid Biofuels	Biogasoline [13]	27.0	13.6	54.0
	Biodiesels [14]	27.0	13.6	54.0
	Other Liquid Biofuels [15]	27.4	13.8	54.0
Gas Biomass	Landfill Gas [16]	50.4	25.4	100
	Sludge Gas [17]	50.4	25.4	100
	Other Biogas [18]	50.4	25.4	100
Other non-fossil fuels	Municipal Wastes (biomass fraction)	11.6	6.80	18.0

Notes:

[1] The lower and upper limits of the 95 percent confidence intervals, assuming lognormal distributions, fitted to a dataset, based on national inventory reports, IEA data and available national data. A more detailed description is given in section 1.5.

[2] Japanese data; uncertainty range: expert judgement

[3] EFDB; uncertainty range: expert judgement

[4] Coke Oven Gas; uncertainty range: expert judgement

[5-7] Japan and UK small number data; uncertainty range: expert judgement

[8] For waste oils the values of "Lubricants" are taken

[9] EFDB; uncertainty range: expert judgement

[10] Japanese data ; uncertainty range: expert judgement

[11] Solid Biomass; uncertainty range: expert judgement

[12] EFDB; uncertainty range: expert judgement

[13-14] Ethanol theoretical number; uncertainty range: expert judgement;

[15] Liquid Biomass; uncertainty range: expert judgement

[16-18] Methane theoretical number uncertainty range: expert judgement;

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Introduction, Volume 2, Chapter 1.

APPENDIX-I

Default Carbon Emission Factor of Fuel from IPCC 2006 Guideline

TABLE 1.4
DEFAULT CO_2 EMISSION FACTORS FOR COMBUSTION [1]

Fuel type English description		Default carbon content (kg/GJ)	Default carbon oxidation factor	Effective CO_2 emission factor (kg/TJ) [2]		
				Default value [3]	95% confidence interval	
		A	B	C=A*B*44/12*1000	Lower	Upper
Crude Oil		20.0	1	73 300	71 100	75 500
Orimulsion		21.0	1	77 000	69 300	85 400
Natural Gas Liquids		17.5	1	64 200	58 300	70 400
Gasoline	Motor Gasoline	18.9	1	69 300	67 500	73 000
	Aviation Gasoline	19.1	1	70 000	67 500	73 000
	Jet Gasoline	19.1	1	70 000	67 500	73 000
Jet Kerosene		19.5	1	71 500	69 700	74 400
Other Kerosene		19.6	1	71 900	70 800	73 700
Shale Oil		20.0	1	73 300	67 800	79 200
Gas/Diesel Oil		20.2	1	74 100	72 600	74 800
Residual Fuel Oil		21.1	1	77 400	75 500	78 800
Liquefied Petroleum Gases		17.2	1	63 100	61 600	65 600
Ethane		16.8	1	61 600	56 500	68 600
Naphtha		20.0	1	73 300	69 300	76 300
Bitumen		22.0	1	80 700	73 000	89 900
Lubricants		20.0	1	73 300	71 900	75 200
Petroleum Coke		26.6	1	97 500	82 900	115 000
Refinery Feedstocks		20.0	1	73 300	68 900	76 600
Other Oil	Refinery Gas	15.7	1	57 600	48 200	69 000
	Paraffin Waxes	20.0	1	73 300	72 200	74 400
	White Spirit & SBP	20.0	1	73 300	72 200	74 400
Other Petroleum Products		20.0	1	73 300	72 200	74 400
Anthracite		26.8	1	98 300	94 600	101 000
Coking Coal		25.8	1	94 600	87 300	101 000
Other Bituminous Coal		25.8	1	94 600	89 500	99 700
Sub-Bituminous Coal		26.2	1	96 100	92 800	100 000
Lignite		27.6	1	101 000	90 900	115 000
Oil Shale and Tar Sands		29.1	1	107 000	90 200	125 000
Brown Coal Briquettes		26.6	1	97 500	87 300	109 000
Patent Fuel		26.6	1	97 500	87 300	109 000
Coke	Coke oven coke and lignite Coke	29.2	1	107 000	95 700	119 000
	Gas Coke	29.2	1	107 000	95 700	119 000
Coal Tar		22.0	1	80 700	68 200	95 300
Derived Gases	Gas Works Gas	12.1	1	44 400	37 300	54 100
	Coke Oven Gas	12.1	1	44 400	37 300	54 100
	Blast Furnace Gas [4]	70.8	1	260 000	219 000	308 000
	Oxygen Steel Furnace Gas [5]	49.6	1	182 000	145 000	202 000

TABLE 1.4 (CONTINUED) DEFAULT CO_2 EMISSION FACTORS FOR COMBUSTION [1]						
Fuel type English description		**Default carbon content (kg/GJ)**	**Default carbon oxidation Factor**	**Effective CO_2 emission factor (kg/TJ) [2]**		
				Default value	**95% confidence interval**	
		A	**B**	**C=A*B*44/12*1000**	**Lower**	**Upper**
Natural Gas		15.3	1	56 100	54 300	58 300
Municipal Wastes (non-biomass fraction)		25.0	1	91 700	73 300	121 000
Industrial Wastes		39.0	1	143 000	110 000	183 000
Waste Oil		20.0	1	73 300	72 200	74 400
Peat		28.9	1	106 000	100 000	108 000
Solid Biofuels	Wood/Wood Waste	30.5	1	112 000	95 000	132 000
	Sulphite lyes (black liquor)[5]	26.0	1	95 300	80 700	110 000
	Other Primary Solid Biomass	27.3	1	100 000	84 700	117 000
	Charcoal	30.5	1	112 000	95 000	132 000
Liquid Biofuels	Biogasoline	19.3	1	70 800	59 800	84 300
	Biodiesels	19.3	1	70 800	59 800	84 300
	Other Liquid Biofuels	21.7	1	79 600	67 100	95 300
Gas biomass	Landfill Gas	14.9	1	54 600	46 200	66 000
	Sludge Gas	14.9	1	54 600	46 200	66 000
	Other Biogas	14.9	1	54 600	46 200	66 000
Other non-fossil fuels	Municipal Wastes (biomass fraction)	27.3	1	100 000	84 700	117 000

Notes:

[1] The lower and upper limits of the 95 percent confidence intervals, assuming lognormal distributions, fitted to a dataset, based on national inventory reports, IEA data and available national data. A more detailed description is given in section 1.5

[2] TJ = 1000GJ

[3] The emission factor values for BFG includes carbon dioxide originally contained in this gas as well as that formed due to combustion of this gas.

[4] The emission factor values for OSF includes carbon dioxide originally contained in this gas as well as that formed due to combustion of this gas

[5] Includes the biomass-derived CO_2 emitted from the black liquor combustion unit and the biomass-derived CO_2 emitted from the kraft mill lime kiln.

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Introduction, Volume 2, Chapter 1.

APPENDIX-J

Default Carbon Emission Factor of Fuel from IPCC 2006 Guideline

TABLE 2.3
DEFAULT EMISSION FACTORS FOR STATIONARY COMBUSTION IN MANUFACTURING INDUSTRIES AND CONSTRUCTION
(kg of greenhouse gas per TJ on a Net Calorific Basis)

Fuel		CO_2			CH_4			N_2O		
		Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper
Crude Oil		73 300	71 100	75 500	r 3	1	10	0.6	0.2	2
Orimulsion		r 77 000	69 300	85 400	r 3	1	10	0.6	0.2	2
Natural Gas Liquids		r 64 200	58 300	70 400	r 3	1	10	0.6	0.2	2
Gasoline	Motor Gasoline	r 69 300	67 500	73 000	r 3	1	10	0.6	0.2	2
	Aviation Gasoline	r 70 000	67 500	73 000	r 3	1	10	0.6	0.2	2
	Jet Gasoline	r 70 000	67 500	73 000	r 3	1	10	0.6	0.2	2
Jet Kerosene		71 500	69 700	74 400	r 3	1	10	0.6	0.2	2
Other Kerosene		71 900	70 800	73 700	r 3	1	10	0.6	0.2	2
Shale Oil		73 300	67 800	79 200	r 3	1	10	0.6	0.2	2
Gas/Diesel Oil		74 100	72 600	74 800	r 3	1	10	0.6	0.2	2
Residual Fuel Oil		77 400	75 500	78 800	r 3	1	10	0.6	0.2	2
Liquefied Petroleum Gases		63 100	61 600	65 600	r 1	0.3	3	0.1	0.03	0.3
Ethane		61 600	56 500	68 600	r 1	0.3	3	0.1	0.03	0.3
Naphtha		73 300	69 300	76 300	r 3	1	10	0.6	0.2	2
Bitumen		80 700	73 000	89 900	r 3	1	10	0.6	0.2	2
Lubricants		73 300	71 900	75 200	r 3	1	10	0.6	0.2	2
Petroleum Coke		r 97 500	82 900	115 000	r 3	1	10	0.6	0.2	2
Refinery Feedstocks		73 300	68 900	76 600	r 3	1	10	0.6	0.2	2
Other Oil	Refinery Gas	n 57 600	48 200	69 000	r 1	0.3	3	0.1	0.03	0.3
	Paraffin Waxes	73 300	72 200	74 400	r 3	1	10	0.6	0.2	2
	White Spirit and SBP	73 300	72 200	74 400	r 3	1	10	0.6	0.2	2
	Other Petroleum Products	73 300	72 200	74 400	r 3	1	10	0.6	0.2	2
Anthracite		98 300	94 600	101 000	10	3	30	r 1.5	0.5	5
Coking Coal		94 600	87 300	101 000	10	3	30	r 1.5	0.5	5
Other Bituminous Coal		94 600	89 500	99 700	10	3	30	r 1.5	0.5	5
Sub-Bituminous Coal		96 100	92 800	100 000	10	3	30	r 1.5	0.5	5
Lignite		101 000	90 900	115 000	10	3	30	r 1.5	0.5	5
Oil Shale and Tar Sands		107 000	90 200	125 000	10	3	30	r 1.5	0.5	5
Brown Coal Briquettes		n 97 500	87 300	109 000	n 10	3	30	n 1.5	0.5	5
Patent Fuel		97 500	87 300	109 000	10	3	30	r 1.5	0.5	5
Coke	Coke Oven Coke and Lignite Coke	r 107 000	95 700	119 000	10	3	30	r 1.5	0.5	5
	Gas Coke	r 107 000	95 700	119 000	r 1	0.3	3	0.1	0.03	0.3
Coal Tar		n 80 700	68 200	95 300	n 10	3	30	n 1.5	0.5	5
Derived Gases	Gas Works Gas	n 44 400	37 300	54 100	r 1	0.3	3	0.1	0.03	0.3
	Coke Oven Gas	n 44 400	37 300	54 100	r 1	0.3	3	0.1	0.03	0.3
	Blast Furnace Gas	n260 000	219 000	308 000	r 1	0.3	3	0.1	0.03	0.3
	Oxygen Steel Furnace Gas	n 182 000	145 000	202 000	r 1	0.3	3	0.1	0.03	0.3
Natural Gas		56 100	54 300	58 300	r 1	0.3	3	0.1	0.03	0.3

TABLE 2.3 (CONTINUED)
DEFAULT EMISSION FACTORS FOR STATIONARY COMBUSTION IN MANUFACTURING INDUSTRIES AND CONSTRUCTION
(kg of greenhouse gas per TJ on a Net Calorific Basis)

Fuel		CO_2			CH_4			N_2O		
		Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper	Default Emission Factor	Lower	Upper
Municipal Wastes (non-biomass fraction)		n 91 700	73 300	121 000	30	10	100	4	1.5	15
Industrial Wastes		n143 000	110 000	183 000	30	10	100	4	1.5	15
Waste Oils		n 73 300	72 200	74 400	30	10	100	4	1.5	15
Peat		106 000	100 000	108 000	n 2	0.6	6	n 1.5	0.5	5
Solid Biofuels	Wood / Wood Waste	n 112 000	95 000	132 000	30	10	100	4	1.5	15
	Sulphite lyes (Black Liquor)[a]	n 95 300	80 700	110 000	n 3	1	18	n 2	1	21
	Other Primary Solid Biomass	n 100 000	84 700	117 000	30	10	100	4	1.5	15
	Charcoal	n 112 000	95 000	132 000	200	70	600	4	1.5	15
Liquid Biofuels	Biogasoline	n 70 800	59 800	84 300	r 3	1	10	0.6	0.2	2
	Biodiesels	n 70 800	59 800	84 300	r 3	1	10	0.6	0.2	2
	Other Liquid Biofuels	n 79 600	67 100	95 300	r 3	1	10	0.6	0.2	2
Gas Biomass	Landfill Gas	n 54 600	46 200	66 000	r 1	0.3	3	0.1	0.03	0.3
	Sludge Gas	n 54 600	46 200	66 000	r 1	0.3	3	0.1	0.03	0.3
	Other Biogas	n 54 600	46 200	66 000	r 1	0.3	3	0.1	0.03	0.3
Other non-fossil fuels	Municipal Wastes (biomass fraction)	n100 000	84 700	117 000	30	10	100	4	1.5	15

(a) Includes the biomass-derived CO_2 emitted from the black liquor combustion unit and the biomass-derived CO_2 emitted from the kraft mill lime kiln.
n indicates a new emission factor which was not present in the 1996 Guidelines
r indicates an emission factor that has been revised since the 1996 Guidelines

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Energy, Volume 2, Chapter 2.

APPENDIX-K

Saturated Water-Temperature Table

Saturated water—Temperature table

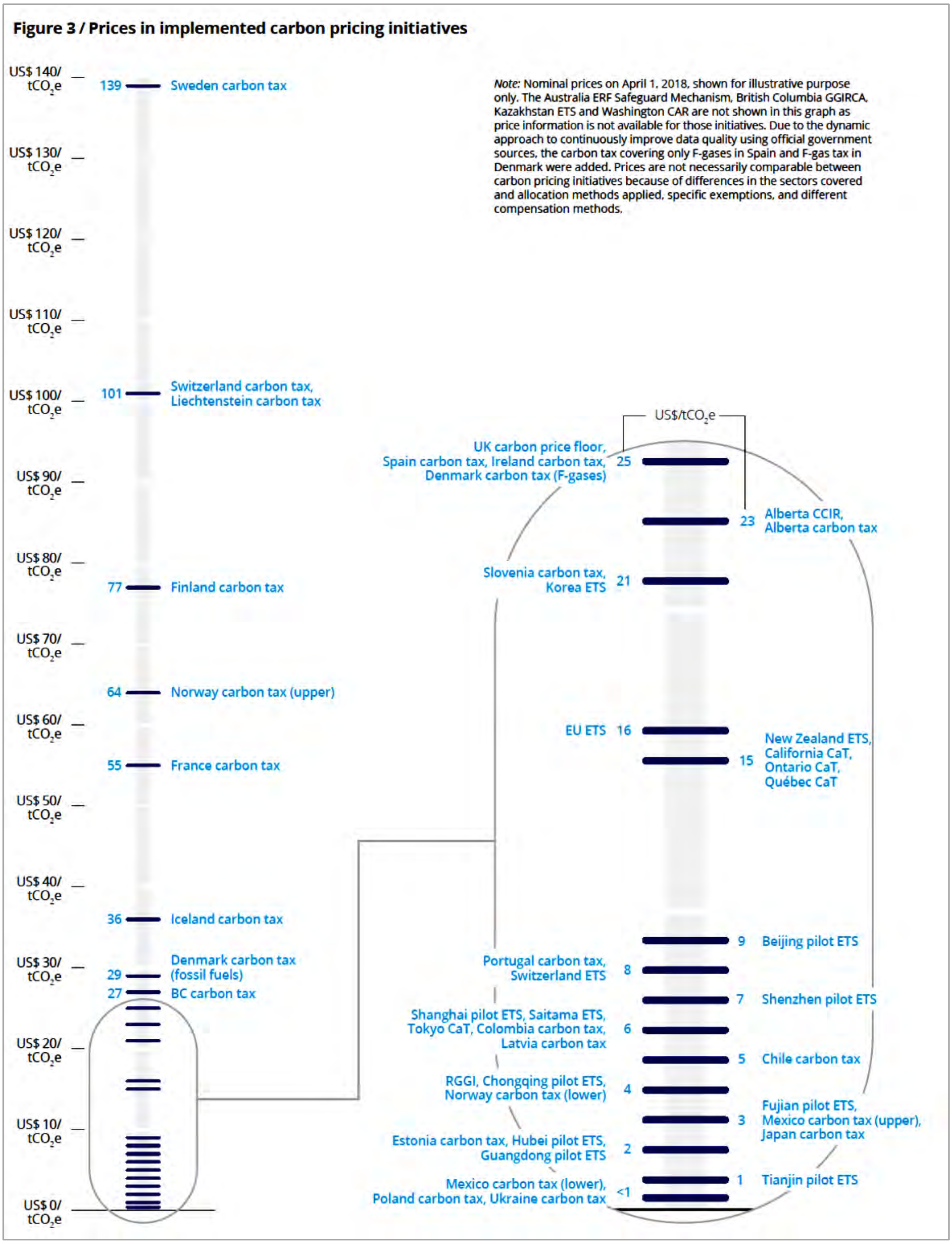
		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292
125	232.23	0.001065	0.77012	524.83	2009.5	2534.3	525.07	2188.1	2713.1	1.5816	5.4956	7.0771
130	270.28	0.001070	0.66808	546.10	1993.4	2539.5	546.38	2173.7	2720.1	1.6346	5.3919	7.0265
135	313.22	0.001075	0.58179	567.41	1977.3	2544.7	567.75	2159.1	2726.9	1.6872	5.2901	6.9773
140	361.53	0.001080	0.50850	588.77	1960.9	2549.6	589.16	2144.3	2733.5	1.7392	5.1901	6.9294
145	415.68	0.001085	0.44600	610.19	1944.2	2554.4	610.64	2129.2	2739.8	1.7908	5.0919	6.8827
150	476.16	0.001091	0.39248	631.66	1927.4	2559.1	632.18	2113.8	2745.9	1.8418	4.9953	6.8371
155	543.49	0.001096	0.34648	653.19	1910.3	2563.5	653.79	2098.0	2751.8	1.8924	4.9002	6.7927
160	618.23	0.001102	0.30680	674.79	1893.0	2567.8	675.47	2082.0	2757.5	1.9426	4.8066	6.7492
165	700.93	0.001108	0.27244	696.46	1875.4	2571.9	697.24	2065.6	2762.8	1.9923	4.7143	6.7067
170	792.18	0.001114	0.24260	718.20	1857.5	2575.7	719.08	2048.8	2767.9	2.0417	4.6233	6.6650
175	892.60	0.001121	0.21659	740.02	1839.4	2579.4	741.02	2031.7	2772.7	2.0906	4.5335	6.6242
180	1002.8	0.001127	0.19384	761.92	1820.9	2582.8	763.05	2014.2	2777.2	2.1392	4.4448	6.5841
185	1123.5	0.001134	0.17390	783.91	1802.1	2586.0	785.19	1996.2	2781.4	2.1875	4.3572	6.5447
190	1255.2	0.001141	0.15636	806.00	1783.0	2589.0	807.43	1977.9	2785.3	2.2355	4.2705	6.5059
195	1398.8	0.001149	0.14089	828.18	1763.6	2591.7	829.78	1959.0	2788.8	2.2831	4.1847	6.4678
200	1554.9	0.001157	0.12721	850.46	1743.7	2594.2	852.26	1939.8	2792.0	2.3305	4.0997	6.4302

Saturated water—Temperature table (*Continued*)

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
205	1724.3	0.001164	0.11508	872.86	1723.5	2596.4	874.87	1920.0	2794.8	2.3776	4.0154	6.3930
210	1907.7	0.001173	0.10429	895.38	1702.9	2598.3	897.61	1899.7	2797.3	2.4245	3.9318	6.3563
215	2105.9	0.001181	0.094680	918.02	1681.9	2599.9	920.50	1878.8	2799.3	2.4712	3.8489	6.3200
220	2319.6	0.001190	0.086094	940.79	1660.5	2601.3	943.55	1857.4	2801.0	2.5176	3.7664	6.2840
225	2549.7	0.001199	0.078405	963.70	1638.6	2602.3	966.76	1835.4	2802.2	2.5639	3.6844	6.2483
230	2797.1	0.001209	0.071505	986.76	1616.1	2602.9	990.14	1812.8	2802.9	2.6100	3.6028	6.2128
235	3062.6	0.001219	0.065300	1010.0	1593.2	2603.2	1013.7	1789.5	2803.2	2.6560	3.5216	6.1775
240	3347.0	0.001229	0.059707	1033.4	1569.8	2603.1	1037.5	1765.5	2803.0	2.7018	3.4405	6.1424
245	3651.2	0.001240	0.054656	1056.9	1545.7	2602.7	1061.5	1740.8	2802.2	2.7476	3.3596	6.1072
250	3976.2	0.001252	0.050085	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7933	3.2788	6.0721
255	4322.9	0.001263	0.045941	1104.7	1495.8	2600.5	1110.1	1689.0	2799.1	2.8390	3.1979	6.0369
260	4692.3	0.001276	0.042175	1128.8	1469.9	2598.7	1134.8	1661.8	2796.6	2.8847	3.1169	6.0017
265	5085.3	0.001289	0.038748	1153.3	1443.2	2596.5	1159.8	1633.7	2793.5	2.9304	3.0358	5.9662
270	5503.0	0.001303	0.035622	1177.9	1415.7	2593.7	1185.1	1604.6	2789.7	2.9762	2.9542	5.9305
275	5946.4	0.001317	0.032767	1202.9	1387.4	2590.3	1210.7	1574.5	2785.2	3.0221	2.8723	5.8944
280	6416.6	0.001333	0.030153	1228.2	1358.2	2586.4	1236.7	1543.2	2779.9	3.0681	2.7898	5.8579
285	6914.6	0.001349	0.027756	1253.7	1328.1	2581.8	1263.1	1510.7	2773.7	3.1144	2.7066	5.8210
290	7441.8	0.001366	0.025554	1279.7	1296.9	2576.5	1289.8	1476.9	2766.7	3.1608	2.6225	5.7834
295	7999.0	0.001384	0.023528	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2076	2.5374	5.7450
300	8587.9	0.001404	0.021659	1332.7	1230.9	2563.6	1344.8	1404.8	2749.6	3.2548	2.4511	5.7059
305	9209.4	0.001425	0.019932	1360.0	1195.9	2555.8	1373.1	1366.3	2739.4	3.3024	2.3633	5.6657
310	9865.0	0.001447	0.018333	1387.7	1159.3	2547.1	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243
315	10,556	0.001472	0.016849	1416.1	1121.1	2537.2	1431.6	1283.4	2715.0	3.3994	2.1821	5.5816
320	11,284	0.001499	0.015470	1445.1	1080.9	2526.0	1462.0	1238.5	2700.6	3.4491	2.0881	5.5372
325	12,051	0.001528	0.014183	1475.0	1038.5	2513.4	1493.4	1191.0	2684.3	3.4998	1.9911	5.4908
330	12,858	0.001560	0.012979	1505.7	993.5	2499.2	1525.8	1140.3	2666.0	3.5516	1.8906	5.4422
335	13,707	0.001597	0.011848	1537.5	945.5	2483.0	1559.4	1086.0	2645.4	3.6050	1.7857	5.3907
340	14,601	0.001638	0.010783	1570.7	893.8	2464.5	1594.6	1027.4	2622.0	3.6602	1.6756	5.3358
345	15,541	0.001685	0.009772	1605.5	837.7	2443.2	1631.7	963.4	2595.1	3.7179	1.5585	5.2765
350	16,529	0.001741	0.008806	1642.4	775.9	2418.3	1671.2	892.7	2563.9	3.7788	1.4326	5.2114
355	17,570	0.001808	0.007872	1682.2	706.4	2388.6	1714.0	812.9	2526.9	3.8442	1.2942	5.1384
360	18,666	0.001895	0.006950	1726.2	625.7	2351.9	1761.5	720.1	2481.6	3.9165	1.1373	5.0537
365	19,822	0.002015	0.006009	1777.2	526.4	2303.6	1817.2	605.5	2422.7	4.0004	0.9489	4.9493
370	21,044	0.002217	0.004953	1844.5	385.6	2230.1	1891.2	443.1	2334.3	4.1119	0.6890	4.8009
373.95	22,064	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

Source: Engineering Equation Solver (EES) software developed by S. A. Klein and F. L. Alvarado

APPENDIX-L
Carbon Pricing Chart



Source: World Bank and Ecofys. 2018. "State and Trends of Carbon Pricing 2018 (May)".