ENTROPY AND THE DEVELOPMENT PROCESS

An Entropic Perspective to Sustainable Development

Thesis submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

RACHNA YADAV

Roll No – 10614109

Department of Humanities and Social Sciences
Indian Institute of Technology Guwahati

Guwahati-781039, India

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DECLARATION

I, Ms. Rachna Yadav, hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Humanities and Social Sciences, Indian Institute of Technology, Guwahati, under the supervision and guidance of Dr. Anamika Barua.

In keeping with the general practice of reporting observations, due acknowledgments have been made wherever the work described is based on the findings of other investigators. The sources of secondary data utilized in this Thesis are duly acknowledged.

RACHNA YADAV

Research Scholar

CERTIFICATE

This is to certify that the thesis entitled "**Entropy and the Development Process – An Entropic Perspective to Sustainable Development**" submitted by **Ms. Rachna Yadav**, **Roll No – 10614109,** for the award of degree of Doctor of Philosophy in the Department of Humanities and Social Sciences of Indian Institute of Technology, Guwahati, embodies bonafide record of research work carried out under my supervision and guidance. The collection of materials from the secondary sources has also been done by Ms. Rachna Yadav herself.

The present Thesis or any part thereof has not been submitted to any other University for the award of any degree or diploma.

All assistance received by the researcher has been duly acknowledged.

Dr. Anamika Barua
Associate Professor
(Thesis Supervisor)

Prof. Mrinal Kanti Dutta
Professor
(Thesis Co-Supervisor)

DEDICATION

To

NICHOLAS GEORGESCU-ROEGEN

Who

ignited the eternal thought

on

ENTROPY LAW

and

ECONOMIC PROCESS

45 Years Ago

ACKNOWLEDGMENT

I would like to express my heartfelt thanks to my Ph.D. supervisor Dr Anamika Barua for her scholarly guidance and constant support throughout the duration of my research work. I shall remain ever grateful to her for introducing me to the subject of Ecological Economics and encouraging me to take up the research on Nicholas Georgescu-Roegen. She also encouraged and guided me to work on the interdisciplinary and challenging topic of linking the Entropy Law and development process. During every crest and trough of my work, she kept the faith and encouraged me to remain focused on my goal. She has been a true guide, mentor and friend, always providing an enabling environment for sound research. I am thankful to her for choosing a highly enlightened group of professors as my doctoral committee members from different disciplines. I wish to thank Prof. Mrinal Kanti Dutta, my co-supervisor for his constant support and encouragement throughout my research work and for providing valuable inputs. He was always available with a helping hand in times of need.

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ABSTRACT

The aim of the thesis is to study and understand the relationship between the laws of thermodynamics and the development process. This has been implemented using the theoretical framework proposed by Nicholas Geogescu-Roegen (NGR) on the Entropy law and the Economic process and applying it to the case of development and urbanization in Guwahati city. According to NGR, all economic processes use low entropy energy and matter as inputs and transform these inputs into high entropy outputs as useful products and wastes. Depletion of low entropy natural resources would pose a limit to economic growth and filling of the natural sinks would also become a limiting factor for the economic processes. Recycling of wastes is also subject to developing appropriate and efficient technologies for waste conversion. Most of the present level of technologies on recycling processes are not very efficient and are also uneconomic. As per the entropy law, 100% recycling and transformation of energy and matter cannot be achieved in real world.

The theory put forward by NGR in 1971 has been debated and the school of thought that accepts his foundation of entropy application in economic processes has emerged as Ecological Economics (1988). The present study makes an attempt to understand and examine the debate surrounding NGR's theories on thermodynamics and economics. While doing so the study also follows and reviews the research studies on NGR in last 45 years. The study has attempted to move beyond the economic process and link entropy with development process and sustainability. In doing so, urbanization, as a unit of development which consumes large quantities of energy and matter that are subjected to processes dissipative in nature and adversely impact the assimilation capacity of the global sinks, has been taken up as a case for study of Guwahati city. Guwahati is not only the largest city of the north east India, but also one of the fastest growing cities in the country. Improved Quality of Life (QoL) and high living standards

leading to development are what attract the people towards urbanization. Development that leads to better QoL is intrinsically linked with high per capita energy consumption and corresponding waste generation in form of waste heat and CO_2 emission. Cities are responsible for 75% of the global energy consumptions and 80% of the GHG emissions (UN-HABITAT, 2007). It is also predicted that by 2040, about 63% of the world population would live in cities (IEA, 2016). Hence, cities also hold the key to sustainable development (Rees, 2003). By adopting right pathways, development strategies, life style changes through efficient use of resources, and reduction in waste generation, they have the potential of addressing climate change mitigation.

The Guwahati city case study has looked at entropy generation and CO_2 emissions, both direct and indirect, in energy, buildings and Agriculture Forestry and Other Land Use (AFOLU) sectors. The study also combines the two factors of waste heat and CO_2 emission into one factor of entropy generation. The study reveals that Guwahati city annually uses 50.42 Peta Joules (PJ) of energy of which 42.84 PJ are lost as waste heat directly and indirectly, in the process generating an entropy of 143.76 Tera Joules per Kelvin (TJK^{-1}) annually. The city also emits 6.31 Million Tonnes CO_2 ($MtCO_2$) annually. The study would help policy makers in taking appropriate policy measures for making Guwahati a sustainable city in the long run. The results of the study would also be useful for further research and decision making for achieving the Sustainable Development Goal No. 11 (SDG 11). It has been seen that the per capita power requirement in the city has gone up from 23 Watts (W) to 117 W within last 15 years. This is directly attributed to the life style change of the people. Development has a direct link with peoples lifestyles, as people are moving towards high consumption phase. The increase in built up area has also negatively impacted the wetlands and forests of the city leading to land degradation and reducing the capacity for carbon sequestration of the forests in and around the city. The city metabolism, and development process has been looked from an entropic perspective. Awareness generation, use of efficient processes, lifestyle changes have been suggested to reduce entropy generation.

One of the main achievements of the study is that it has taken forward the theory of NGR on the Entropy law and the economic process relationship a step ahead by applying his theoretical framework onto the development process, and helping in understanding sustainable development from entropy perspective. The study enriches the existing transdisciplinary research in the area of ecological economics. This is the first research study of Guwahati from entropy perspective. It is unique as it combines waste heat and CO_2 emission together into one using entropy, making a single entropic indicator of climate change which could directly correlate with global warming. The framework developed for conducting the city case study adopts a simple approach and can be taken up for similar studies elsewhere. The study brings to fore that NGR was prophetic and ahead of his times. The study has helped in asserting the re-emergence of NGR's theory, concepts and thinking within the ambit of the development agenda and climate change discourse.

LIST OF PUBLICATIONS

Refereed Publications

Yadav R, Barua A, 2015	A study of urbanization and ecosystem services of Guwahati city from forest footprint perspective, *Journal of Ecosystem & Ecography, Global Climate Change*, 2016, S5, http://dx.doi.org/10.4172/2157-7625.S5-004
Rachna Yadav Anamika Barua, 2017	Contribution of Urbanization to Emissions: Case of Guwahati City, India, in *Urban Ecology, Water Quality and Climate Change*, Ed. Arup K. Sarma, Vijay P. Singh, Rajib K Bhattacharjya, Suresh A. Kartha, Water Science and Technology Library, Volume 84, Springer, 2018, ISBN 978-3-319-74493-3

Paper under Peer Review

Yadav R, Barua A, 2017	Circular Economy For Sustainable Development: A Case Of Cement Industry, *Global Sustainability*, Cambridge University Press

Conference Papers

Rachna Yadav Dr. Anamika Barua, Prof. Joyashree Roy, 2016	Urbanization, Resource use and Rise in Entropy: A Case Study of Guwahati City, Eighth Biennial Conference INSEE, Urbanization and the Environment, January, 4-6, 2016, Bengaluru, *https://goo.gl/6NzLYJ*
Rachna Yadav Anamika Barua, 2012	A Study of (Un)Sustainable City from Entropy Perspective, 2012 ISEE Rio+20 International Conference: Challenges and contributions for a Green Economy, Rio de Janeiro, June 16-19, 2012. *www.isecoeco.org/conferences/isee2012-versao3/pdf/957.pdf*
Yadav R, Barua A, 2012	A Study of Urbanization and Ecosystem Services of Guwahati City from Ecological (Forest Ecosystem) Footprint Perspective, ENSURE 2012, International Conference on Environmentally Sustainable Urban Ecosystems, February 24-26, 2012, Guwahati, Assam

Conferences / Trainings Attended

Conclave on Sustainable Development Goals for environment and Climate Change, Sustainable Consumption and Production (Goal-12), Climate Action (Goal-13), Conservation of Water Resources (Goal-14), Life on Land (Goal-15), Assam Administrative Staff College, Khanapara, Guwahati, 2017, 14-15th July, 2017

Developing Skill and Knowledge – training workshop on transboundary Brahmaputra river, 13th -14th June, 2017, SaciWATERs & C-NES, Guwahati, Assam

Bilateral Dialogue on the management of Brahmaputra River Basin, 6th August, 2015, NEDFi House, SaciWATERs, The Asia Foundation, Guwahati, Assam

National Workshop On Gender Budgeting in Rural Development, 25-27, February, 2015, National Institute of Rural Development, NERC, Guwahati

Workshop on Roadmap for sound management of E-Waste, Guwahati, 21st November, 2014, PCBA & Toxic Link, http://goo.gl/5e3z3G

National Workshop On Gender Budgeting, 26-28, February, 2014, National Institute of Rural Development, NERC, Guwahati, *icds-wcd.nic.in/gb/material/Training/2013-2014/29.pdf*

Training programme on the global development agenda: tools for gender-sensitive planning and implementation, Distance learning programme – network learning Modality, 2nd September to 2nd December, 2013, International Training Centre (**ITC**), International Labor Organization (**ILO**), **Turin, Italy**

Winter Course in **Ecological Economics**, Environment Europe, St. Hugh's College, **University of Oxford**, 17-21 December, 2012, Oxford, **UK**.

ISEE Conference and **Rio+20**: Challenges and Contributions for a Green Economy, 16-19 June, 2012, **Rio de Janeiro, Brazil**

Ensure 2012 International Conference on Environmentally Sustainable Urban Ecosystems, February 24-26, 2012, Guwahati, Assam

IUCN International Workshop on Ecosystems for Life: Food Security, Water Productivity, Poverty & Climate Change, 20-23 November, 2011, **Dhaka**

INSEE Conference on Nature, Economy & Society: Understanding the Linkages, October 20-22, 2011, Hyderabad

Pre-Conference **INSEE Workshop on** 'Pathways to Interdisciplinarity: Analyzing the Interface of Nature, Economy and Society' October 19, 2011, Hyderabad

International Conference on Climate Change and Water: Assessing vulnerability, impact & adaptation in the eastern Himalayas, 3-5 January, 2011, Deptt HSS, IIT Guwahati

ACRONYMS AND ABBREVIATIONS

3R	Reduce Reuse Recycle
4R	Reduce Reuse Recycle Replace
AD	Anno Domini
AEGCL	Assam Electricity Grid Corporation Ltd.
AFOLU	Agriculture, Forestry & Other land Uses
AHF	Anthropogenic Heat Flux
APDCL	Assam Power Distribution Company Ltd.
AR	Assessment Report (AR1, AR2, AR3,…) of IPCC
ASEB	Assam State Electricity Board
AT	Assam Type
BA	Built Up Area
BAU	Business As Usual
BEE	Bureau of Energy Efficiency
BP	British Petroleum, Building Permission
CCS	Carbon Capture Storage
CDIAC	Carbon Dioxide Information Analysis Center
CE	Circular Economy
CEA	Central Electricity Authority
CKD	Clinker Kiln Dust
CKD	Cement kiln Dust
CL	Cropland
CoP	Conference of Parties
CRRI	Central Road research Institute of India
CRS	Coordinate Reference System
CSD	Commission on Sustainable Development
DoP	Date of Pass
DP	Development Process
DTR	Distribution Transformer
EE	Ecological Economics
EF	Emission Factor
EDGAR	Emission Database for Global Atmospheric Research
EGPC	Entropy Generation Per Capita
EJO	Environmental Justice Organisations
EKC	Environmental Kutznets Curve
EP	Economic Process
EU	European Union

F&CS	Food and Civil Supplies
FCBTK	Fixed Chimney Bull's Trench Kiln
FD	Fuel Density, Forest Department
FL	Forest Land
FLE	First Law Efficiency
FOLU	Forestry and Other Land Use
FS	Forest to Settlement
FSI	Forest Survey of India
FW	Fuelwood
G&S	Goods and Services
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GF	Ground Floor
GFN	Global Footprint Network
Gg	Giga (10^9) Grammes
GHG	Green House Gases
GIREM	Global Initiative for Restructuring Environment & Management
GIS	Geographic Information System
GL	Grassland
GMA	Guwahati Metropolitan Area
GMC	Guwahati Municipal Corporation
GMDA	Guwahati Metropolitan Development Authority
GNP	Gross National Product
GPI	Genuine Progress Index
GST	Global Surface Temperature
Gt	Giga (10^9) Tonnes
GWP	Global Warming Potential
Ha	Hectares
HDI	Human Development Index
HEONS	Heat Equivalents of Noxious Substances
HH	House Holds
HLPF	High Level Political Forum
HSD	High Speed Diesel
IBEF	India Brand Equity Foundation
ICE	Inventory of Carbon and Energy
ICIP	Institut Catala Internacional per la Pau
ICLEI	International Council for Local Environmental Initiatives [now ICLEI - Local

	Governments for Sustainability]
IEA	International Energy Agency
IETD	Industrial Efficiency Technology Database
IGES	Institute for Global Environmental Strategies
IIASA	International Institute for Applied Systems Analysis
IOCL	Indian Oil Corporation Ltd.
IPCC	Intergovernmental Panel on Climate Change
INSEE	Indian Society for Ecological Economics
ISEE	International Society for Ecological Economics
ISIC	International Standard Industrial Classification of All Economic Activities
K	Kelvin
KL	Kilo Litres
KOIL	Kerosene Oil
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LPG	Liquid Petroleum Gas
LULUCF	Land Use Land Use Change and Forestry
MS	Motor Spirit (Petrol)
MSL	Mean Sea Level
MT	Metric Tonnes
MT	Metric Tonnes
$MtCO_2$	Million Tonnes Carbon Dioxide
MTPA	Million Tonnes Per Annum
MU	Million Units
NASA	National Aeronautics and Space Administration
NCE	Neo Classical Economists
NCV	Net Calorific Value
NE	North East
NGR	Nicholas Georgescu-Roegen
NITI	National Institution for Transforming India
NOAA	National Oceanic and Atmospheric Administration, US
NSSO	National Sample Survey Organization
NTP	Normal Temperature Pressure

NW	North West
OECD	Organisation for Economic Co-operation and Development
OF	Other Floors
OL	Other Lands
OTG	Off The Grid
PCP	Per Capita Power (Watts Per Capita)
PDCR	Production Distribution Consumption and Reduction
PIDS	Philippine Institute for Development Studies
PJ	Peta (10^{15}) Joules
PM	Prime Minister
PMM	Perpetual Motion Machine
ppm	Parts Per Million
ppmv	Parts Per Million by Volume
PWD	Public Works Department
QGIS	Quantum GIS
QoL	Quality of Life
R^2	Coefficient of Determination
RCC	Reinforced Cement Concrete
RF	Reserved Forest
RFFP	Rain-Fed Flood Plain
RMS	Root Mean Square
RSS	Residual Sum of Squares
RTI	Research Triangle Institute now RTI International
SCM	Smart City Mission
SDG	Sustainable Development Goals
SE	South East
SEC	Specific Energy Consumption
SHR	Station Heat Rate
SL	Settlements
SLE	Second Law Efficiency
SNIO	Sub National Input Output Analysis
Sq Km	Square Kilo Meters
SW	South West

TJ	Tera (10^{12}) Joules
TM	Thematic Mapper
TPP	Thermal Power Plant
U	Unit (1U = 1 kWh)
UAE	United Arab Emirate
UK	United Kingdom
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNDSD	United Nations Division on Sustainable Development
UNFCCC	United Nations Framework Convention on Climate Change
UNFPA	United Nations Population Fund, formerly the United Nations Fund for Population Activities
US	United States of America
USDoE	US Department of Energy
USF	Unclassed State Forests
USGS	United States Geological Service
UTM	Universal Transverse Mercator
VKT	Vehicle Kilometer Travel
W	Watt
WB	World Bank
WCED	World Conference on Economic Development
WL	Wetland
wrt	with respect to
WRI	World Resource Institute
WWF	World Wide Fund for Nature and Nature Conservation

Symbols Used and Their Meanings

ΔE	Change in Internal Energy (also Energy Waste)
Q	Heat exchanged
W	Work done, (also Watts)
T	Temperature
ΔS	Change in Entropy
E_{output}	Useful Energy (Output, or useful service)

E_{input}	Energy pumped (input)
η	Efficiency
Qc	Heat lost to the surrounding (cold)
Q_H	Heat transferred by the hot body
M_{input}	Mass input to the system
M_{output}	Mass output (useful Goods)
ΔM	Waste mass (in solid, liquid or gaseous forms)
C_P	Heat capacity at constant pressure
S_T	Entropy due to translation
S_R	Entropy due to rotation
S_v	Entropy due to vibration
S_E	Entropy due to electronic spin motion
S_N	Entropy due to nuclear spin motion
F_{CO2}	Amount of CO_2 released per unit of consumption of fuel
ΔE_{LOSS}	Energy loss (^{o} heat loss)
$E_{Theoretical}$	Theoretical Energy required for a process
P	Population (in millions)
E_{HH}	Energy at HH level in MU
A_{FS}	Area (in Sq km) of forest diverted to settlement
A_{FW}	Amount of fuelwood consumed in tonnes
A_{CL}	Area under cropland (in sq km)
A_{WL}	Area of wetland (in sq km)

Units and Conversion Factors: International System of Units (SI) Prefixes

Prefix SI Name	Symbol	Multiplication Factor
Exa	E	10^{18}
Peta	P	10^{15}
Tera	T	10^{12}
Giga	G	10^{9}
Mega	M	10^{6}
kilo	k	10^{3}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}

Other National/ International Prefixes

Prefix Name	Symbol	Multiplication Factor
Million	M	10^6
Billion	B	10^9
Trillion	T	10^{12}
Lakh	lakh	10^5 (=0.1M)
Crore	cr	10^6 (=1M=10 lakh)

International System of Units (SI) Basic Units & Derived Units

Physical Quantity	SI Unit	Symbol	Definition/ Equivalence
Length	meter	m	
Mass	kilogram	kg	=1000g (g→Gramme)
Volume	litre	l	=1000 ml =1000 cc (cubic centimeter)
Time	second	s	
Temperature	Kelvin	T	0^0C=273.15K (^{0}C→ Degree Celsius)
1 Avogadro quantity	mole	mol	$6.022140857 \times 10^{23}$ units of substance ≡ 1 mol
Energy	joule	J	≡ kgm^2s^{-2} ≡ 0.239006 cal (cal→calories)
Power	watt	W	Js^{-1}
Entropy			JK^{-1}
Molar Entropy			$JK^{-1}mol^{-1}$
Area	hectare	ha	=10000 m^2 = 0.01 km^2 = 2.47 acres
Mass	tonne	t	1000 kg

Other Units

Physical Quantity	Unit	Symbol	Definition/ Equivalence
Temperature	Degree Celsius	^{0}C	0^0C=273.15K (K→ Kelvin)
Mass	Mega tonnes	Mt	=10^6t = 10^9kg = 10^{12}g = 1Tg
Mass	Giga Grammes	Gg	=10^9g = 10^6kg = 10^3t
Time	Year	yr	=365.25 days =8766 hours = 31557600 seconds
	Hour	h	=3600 s (24 h = 1 day)
Energy	calorie	cal	=4.184 J
Parts per million	ppm	ppm	μmol $mole^{-1}$
	Ppmv (volume)	ppmv	μl l^{-1}
Electricity (Energy)	Units	U	=1kWh = 3.6MJ
	Million Units	MU	=10^6kWh=1 GWh=3.6TJ
	Metric ton of Oil Equivalent	toe	=4.1868×10^{10}J =11630 kWh = 1.42857143 tce
	Million ton Oil Equivalent	Mtoe	=4.1868×10^{16} J = 11630 Gwh = 0.041868 EJ = 41868 GJ = 1.42857143 Mtce
	Metric ton of Coal	tce	293076×10^5J = 8141 kWh = 0.70 toe

Equivalent		
Million ton of Coal Equivalent	Mtce	293076×10^{11}J = 8141 GWh = 0.70 Mtoe
British Thermal Unit	Btu	=1055.05585J = 251.995761 cal

Fundamental Constants

Physical Quantity	**Symbol**	**Unit**	**Value/ Definition/ Equivalence**
Avogadro Number	N_A	mol^{-1}	$6.022140857 \times 10^{23}$
Stefan-Boltzmann constant	σ	$Wm^{-2}K^{-4}$	5.67051×10^{-8} ($=2\pi^4k^4/15h^3c^2$)

Useful Quantities and Standard Values of the Earth-Sun System

Physical Quantity	**Symbol**	**Unit**	**Value**
Solar Constant	S	wm^{-2}	1367
Earth Mass	M	kg	5.976×10^{24}
Equatorial radius	a	m	6.378×10^{6}
Polar radius	c	m	6.357×10^{6}
Mean radius	R	m	6.371×10^{6}
Mean distance from Sun to Earth		m	149597870691
Sun mass		kg	1.989×10^{30}
Sun surface temperature		K	5778
Sun radius		m	695700000
Surface area of the earth		m^2	5.101×10^{14}
Land area of the earth		m^2	1.481×10^{14}
Ocean area		m^2	3.620×10^{14}
Mass of atmosphere		kg	5.137×10^{18}
Moles of air			1.8×10^{20}
Ocean mass		kg	1.384×10^{21}
Mean Ocean volume		m^3	1.350×10^{18}
Mass of troposphere		kg	4.11×10^{18}
Mass of stratosphere		kg	0.5×10^{18}
Height of troposphere		km	12

Other Useful Quantities and Values

Physical Quantity	**Symbol**	**Unit**	**Value/ Definition/ Equivalence**
Value of Pi	π		3.14159265359
Value of e	e		2.71828182846
Standard Ambient Temperature		K	298.15 (earlier it was 0^0C)
Standard pressure		bar	1 (= 10^5 Pa)

Molar volume of gas at STP	$l\ mol^{-1}$	22.414
Density of dry air at STP	$Kg\ m^{-3}$	1.293

Common Conversion Factors

From	**To**	**Factor**
1 acre	m^2	4047
	ft^2	43560
1 hectare (ha)	Acre	2.470966
1 atmosphere pressure (atm)	mmHg	760
	Millibars (mb)	1013.25
1 bar	atm	0.98692
1 litre	m^{-3}	0.001
1 m^{-3}	Litre	1000

FACTORS FOR CARBON & CARBON DIOXIDE:

1 mole CO_2 = 44.0095 g CO_2 = 12.0107 g C

1 g C = 0.083 mole C = 3.664 g CO_2 (1gC ≅ 3.67 CO_2)

1 ppmv of CO_2 = 2.13 Gt C = 7.804 Gt CO_2

Atomic Weight of Carbon = 12.0107

Atomic Weight of Oxygen = 16.000

No. of Moles of CO_2 in 1 g CO_2 = 1/44.0095 = 0.0227 g

Molar Entropy of CO_2 at 298 K = 213.69 $JK^{-1}Mole^{-1}$

Entropy of 1 g of CO_2 at 298 K = 4.86 JK^{-1}

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CHAPTER 1

1 Introduction

The destiny of the human species is to choose a truly great but brief, not a long and dull career (NGR, 1971, p304)

1.1 Setting the Research Context

The present thesis is primarily based on the works of Nicholas Georgescu-Roegen (4^{th} February, 1906 - 30^{th} October, 1994), in short referred to as NGR, who first put forth the thermodynamic basis of all economic activity. He was a Romanian-American mathematician, statistician and economist, and is best known for his magnum opus "The Entropy Law and the Economic Process" published in 1971. His mentor was Joseph Schumpeter (8^{th} February 1883 – 8^{th} January 1950), an Austrian-Hungarian-American economist and political scientist. NGR was a known critique of neoclassical production theory for its neglect of natural resources. The theories of NGR center around application of the Entropy Law, known as the Second Law of Thermodynamics, in the economic processes. Entropy is a measure of dispersal of energy, and the term "high entropy" refers to low quality energy, while "low entropy" refers to high quality energy (Glucina & Mayumi, 2010). The premise of the thesis of NGR rests on the principle that the economic process is a continuous and irrevocable transformation of low entropy to high entropy which has some serious consequences. NGR calls growth and development as "entropic struggle of man", and the entropy law as principal cause of economic scarcity (NGR, 1971, Tsuchida, 1999). Continuous supply of low entropy matter and energy on one hand and discarding waste and waste heat into surroundings on the other are what make a system unsustainable, causing environmental damage which means damaging nature's cycles (Tsuchida, 1999). Post Industrial Revolution (Anthropocene[1] era) human actions have become the main drivers of global environmental change and atmospheric CO_2 concentrations rising much beyond the pre-industrial value of 280 ppmv (Rockstrom et al, 2009). Given the continued dominance of fossil fuels in the world economic growth, CO_2 emissions are expected to increase rapidly by 2040 (IEA, 2016). Today's biggest concern gripping the world leadership is climate change, which was reflected in the Conference of Parties (CoP) 21 meeting in Paris in December, 2015 and signing of *Accord de Paris* by more than 190 countries, and its ratification in November, 2016. The Paris Declaration clearly speaks that "… *climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries, and their participation in an effective and appropriate international response, with a view to accelerating the reduction of global greenhouse gas emissions…* ". The CO_2 level in the atmosphere has been reckoned to be at 280 ppm in 1800 at the beginning of the Industrial revolution, and has since then continued to rise as manifested by increased global surface temperature and rising sea level (IPCC, 2007). As per the latest report from the Mauna Loa Observatory, Hawaii, the atmospheric CO_2 has touched 409.65 ppm as of May, 2017. The IPCC Synthesis Report 2014, Summary for Policy Makers (AR5) states that "*Human influence on the climate system is clear, and recent anthropogenic emissions of green house gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems*". It further states that "*Anthropogenic gas emissions have increased since the pre-industrial era driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of* CO_2*, methane, nitrous oxide that are unprecedented in at least the last 800,000 years*" (IPCC, 2014). Thus, the energy and matter consumed in economic growth and development turn into waste energy and matter which are

1 Anthropocene is a proposed epoch of significant human activity comparable to geological scale, with a lower boundary, still to be formally identified but suitably placed in the mid-20th century (Waters et al, 2016)

entropic in nature and stay for long in highly dispersed state causing global warming and climate change, posing challenges to sustainable development.

1.1.1 Climate Change as a Challenge to Sustainable Development

The most quoted definition of Sustainable development by WCED "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). This definition, in fact, has within it embedded the source-sink[2] concerns emerging due to rapid energy matter conversions by the economic growth engine which ushers in Development but its negative environmental impacts and anthropogenic emissions have put constraints on sustainable development. The 1987 WCED was a run up to the Rio earth Summit in 1992 with an agenda to make the Commission on Sustainable Development (CSD) to pursue the sustainable development agenda vigorously. However, nothing much happened. In 2012, finally in the Rio+20 summit, the High Level Political Forum (HLPF) was constituted to facilitate implementation of Agenda 2030 and its Sustainable Development Goals. As per the UN SDG (UN-DSD, 2016) Report, "*Climate change presents the single biggest threat to development, … urgent action to combat climate change and minimize its disruptions is integral to the successful implementation of the sustainable development goals*". As discussed in the previous paragraph, there is sufficient evidence to say that anthropogenic activities are the main drivers of climate change which poses the biggest threat to sustainable development. The human economy used 21,179 EJ[3] of energy from 1800 to 2008 (Smil, 2010), and 573 EJ being the consumption for 2014 alone (IEA, 2016). The total anthropogenic carbon emission from 1750 to 2011 was 555 GtC, while that for 1870 to 2011 was 515 GtC (IPCC, 2013, UNFCCC, 2015), giving pre-industrial emission rate during 1750-1870 at

2 Biosphere is seen as source when talked in terms of natural resource extraction, and seen as sink when talked in terms of its assimilation capacity for waste heat and pollutants

3 Adapted from Appendix of Smil (2010) by summing up energy values in EJ from 1800 to 2008, with value of energy used in 1800 being 20.35 EJ and in 2008 being 456.41 EJ (*Sources of energy accounted: Coal, Crude oil, Natural gas, Hydro, Nuclear & Biofuels*)

0.33 GtC yr^{-1}, and from 1870-2011 at 3.65 GtC yr^{-1}. The emission rate for 2010 stood at 13.35±1.23[4] GtC. Given the alarming rise in CO_2 levels, it was in the 15th Conference of Parties (CoP) meeting at Copenhagen in 2009 (UNFCCC, 2010) that the member countries signed the Copenhagen Accord to cut green house gas emissions to keep the mean global surface temperature below 2^0 C of the pre-industrial stage, and reiterated further in Cancun Accord of the 16th CoP (UNFCCC, 2011), which meant keeping the atmospheric CO_2 levels below 450 ppmv (IEA, 2011). The projected energy consumption in 2040 may not come below 748 EJ (and 9.9 GtC emission) whereas the desired levels ideally should be 623 EJ and 5 GtC emission[5] (IEA, 2016). Such high energy consumption forces one to explore if economic growth and development are going beyond limit.

1.1.2 Biophysical Limits and Development – Are We Overshooting?

Increase in resource consumption propelled by globalization is leading to more and more people worldwide, especially Asian countries to move to the living standards of the western world. Based on the Global Footprint Network data of 2011, and using the terrestrial footprint only, Tim De Chant (2012) worked out that if all the people on the earth would live as an American, then 4.1 earths would be necessary and if they lived like an UAE citizen, then 5.4 earths would be needed. Given the limited resources on the planet earth and the present existing levels of technology, providing the high standard of living of the western world to the developing nations appear impossible. *At the same time it is unethical to deny a similar standard of living to the people outside the western world*. This is the dilemma of our times. (Florin Bonciu, 2014). This dilemma has been examined in more detail from source-sink perspective in the next section.

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4 IPCC AR5 (2014) lists emission for 2010 at 49±4.5 $GtCO_2$ which is converted to GtC using conversion factor of 3.67 (Page 6). The fossil fuel related emissions stood at 32 (±2.7) $GtCO_2$/yr in 2010 amounting to 8.72±0.74 GtC.

5 IEA WEO (2016) predicts energy consumption level of 17866 Mtoe (748.014 EJ) in 2040 in new policy scenario with 36.3 $GtCO_2$ (9.89 GtC) emissions, and 14878 Mtoe (622.912 EJ) energy consumption and 18.4 $GtCO_2$ (5.01 GtC) in 450 scenario. Values converted using appropriate factors.

1.1.3 Development Process: Resource Depletion and Sink Assimilation Challenges

In simple terms development is defined as improvement in the Quality of Life (QoL) or improving the standard of living of communities. The most commonly used development measure being the Human Development Index (HDI) which basically is an improvement in the income, health and education (UNDP, 2015). Improvement of the three basic parameters/ indicators mentioned above for communities in the real world calls for huge investments and supply of resources in the form of energy and matter which impact the ecosystems negatively. Wakernagel et al (2005) and Rees (1996) through their Ecological footprint measure have pointed out that human societies crossed the threshold level and their "overshoot" symptoms are visible in the biophysical world. The notion of scarcity as a constraint of economic growth goes back to Malthus. It was only later that other natural resources, especially exhaustible resources began to be seen as factors of production (Ayres, 2001). There have been a number of actual resource scarcity, even exhaustion- usually limited to a particular resource or country. A few examples are charcoal in Europe, coal in Britain, sperm whales, used as a source of lamp oil. (Ayres, 2001). Extraction of crude oil peaked[6] in 2006. Production is declining 4-6% per year in fields discovered in 1960s (Sylvia Lorek, 2014). It is predicted that crude oil may finish in another 52.5 years. The natural gas is predicted to be sufficient to meet the global needs only by another 54.1 years (BP, 2015). Substitutability is always not possible as some resources are required in massive quantities and also a particular form of energy may alone be possible to be used by certain modes. The energy supply sector is the largest contributor to global greenhouse gas (GHG) emissions. Despite the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, annual GHG emissions growth from the global fossil fuels accelerated from 2.5 GtCO_2/yr in 1990-2000 to 6.8 GtCO_2/yr in 2000-2010 (IPCC, 2015). On

6 "Peak Oil" phenomenon is now being followed by "peak phosphorus" (Martinez-Alier, 2012)

the material source side, some of the elements that would be depleted in next 5 to 50 years include gold, platinum, silver, tungsten, zinc, manganese, tin and antimony, whereas chances of lithium, magnesium, aluminum, phosphorus, sulfur, cobalt, nickel and copper beyond 50-100 years are bleak. Further, elements such as lithium, beryllium, vanadium, strontium are capable of being recycled upto less than 1%. Elements such as silver, cobalt, nickel, copper, platinum and manganese can be recycled upto more than 50% (Clark J, 2015). According to Professor James Clark (2015), "*… Like with petroleum we have used up most of the easy reserves and whats left is going to be in increasingly difficult places which we will only be able to exploit at high economic and environmental cost.*" On the sink side, the CO_2 released by burning of fossil fuels and deforestation is absorbed by the atmospheric and oceanic sinks, as well as getting consumed in greening. Atmosphere absorbs about 3.3 Gt carbon (52%), while the ocean absorbs about 2.1 Gt (33%). Carbon absorbed in greening is about 1 Gt (15%) (Broecker & Peng, 1998). As per latest estimates, 32.4±1.6 $GtCO_2$ is released annually from fossil fuels and cement. About 44% of the CO_2 is absorbed by the atmosphere. A net of 15.8±0.4 $GtCO_2$ remains in the atmosphere leading to global warming (Le Quere et al, 2014). The year 2016 has been the warmest year since 1880. Since the start of the 21st century, the annual global temperature record has been broken five times - 2005, 2010, 2014, 2015, and 2016 (NOAA, 2017). Thus, the premise of this Thesis is derived from the Laws of Thermodynamics that put a biophysical limit to perpetual growth, as propounded by NGR in 1971, and puts forth the argument that entropy is intimately linked with climate change and sustainable development.

1.1.4 Entropy Law and Climate Change

Energy intensity is a measure of economic activity and energy use, or more precisely the ratio of energy use to GDP. Economic activity is linked to energy, largely from fossil fuels, which in turn lead to emissions, implying an urgent need to decouple economic growth from energy use

(Ockwell, 2008). Further, there is a challenge to reduce energy intensity at rates that are faster than historical norms and that energy intensity improved far slower than the rate of economic growth and so energy use tends to increase with growth (Csereklyei, Varas, and Stern, 2016). Though the recent data show a significant slowdown in the growth of energy-related CO_2 emissions in 2014 and 2015, but making it a sustained fall is a challenge. Along with decoupling economy from energy, there is another task to decarbonize the energy itself by resorting to low carbon energy. Improvements in energy intensity and deployment of low carbon footprint energy have to reach higher in order to substantially lower emissions, but the net result is still a stiff upward trend in global demand for energy (IEA, 2016). Decarbonizing energy, say for 160 $MtCO_2$ reduction, would mean replacing 40 large coal-fired power plants with zero-carbon electricity; or replacing more than 50 million cars each year with electric vehicles, charged with zero-carbon electricity. However, decarbonizing energy only would reduce CO_2 levels, but the generation of waste heat would continue, if system efficiencies are not taken care of, as the Entropy Law would be operating on all forms of energy. Therefore, a “Triple Play” strategy needs to be put in place: 1. Decouple economy from energy, 2. Decarbonize energy & 3. Improve system efficiencies. Thus, anthropogenic waste heat and emissions have direct bearing on the climate and global surface temperature. McKitrick & Michael (2007) studied the trends in measured surface temperatures across 440 locations around the world from 1979 to 2002, and concluded that trends in gridded climate data[7] correspond to the socio-economic activities of the region. De Laat and Maurellis (2003) concluded that rise in surface temperatures spatially correlated to anthropogenic surface CO_2 emissions which is a measure of industrialization. Flanner (2009) and Ming Cai et al (2013) have shown that the anthropogenic heat flux (AHF) though averages to only 0.028 Wm^{-2}, has its impact felt miles away from the source, and the climate models need to account for it. According to IPCC (2001), since 1950s the overall global

7 $5^0 x 5^0$ grid based temperature measurements across the world since 1979

temperature increases in the lowest 8 kilometers of the atmosphere and in surface temperature have been 0.1°C per decade. Bennewitz (2007) estimated that the global surface temperature rise could be well accounted by way of entropy generation from all forms of energy use since 1750 AD. It is, thus, seen that energy use, which drives economic growth, gives rise to entropy and thus contributes to climate change. However, to substantiate the argument and take the premise of NGR further to link it closely with development process, this Thesis examines urbanization as a case of development process, which as a case study has been elucidated in the next two paragraphs briefly to set the right context.

1.1.5 Urbanization: A Case of Development Process

The thesis further explores NGR's concepts on thermodynamics and economics in the light of a city sub system, taking urbanization as a development process which are dissipative, complex structures, and growth engines which feed on large quantities of energy and matter and their transformations/ conversions. With more than 50% of the global population now residing in Cities, they play a dominant role in GHG emission reduction. Cities could impact sustainable development both ways - either they could negatively impact sustainable development if not managed well or could hold the solution to global sustainability (Rees et al, 2013). While talking of progress on SDG 11 - Make cities and human settlements inclusive, safe, resilient and sustainable, the UN SDG Report says, "*More than half of the world's population lives in cities. By 2030 it is projected that 6 out of 10 people will be urban dwellers. … Despite numerous planning challenges, well managed cities and other human settlements can be incubators for innovations and ingenuity, and key drivers for sustainable development*" (UN-DSD, 2016).

1.1.6 Sustainable Development and Sustainable City

In the paragraph above, the development and urbanization linkage has been dealt with briefly.

While urbanization is considered as one of the main drivers of climate change, it also holds the key to sustainable development. In order to do so, the concept of sustainable city or eco-city is emerging. Sustainable cities work towards “an environmentally, socially and economically healthy and resilient habitat for existing populations, without compromising the ability of future generations to experience the same” (ICLEI, 2015). Cities that pursue carbon neutrality and support active green economy and stable green infrastructure are called low carbon cities. A sustainable city is one for which the inflow of material and energy resources, and the disposal of wastes, do not exceed the capacity of the city’s surrounding environment (Kennedy et al, 2007). Sustainable cities reduce natural resource consumption and waste production footprints, and that they improve land-use efficiencies (EC, 2015). The present study examines some of these issues of sustainability with reference to city, taking Guwahati city (India) as a case study.

1.2 Finding the Research Gaps

Against the backdrop and context described in paragraphs above, it can be seen that energy is indispensable for human development and economic growth (GEA, 2012). Fossil fuels and non renewable energy sources are constraints that pose a limit for economic growth, if growth is taken to mean increasing production and consumption of physical goods (Krysiak, 2006). Energy and matter interactions are subject to the Laws of Thermodynamics. The biophysical limits to economic growth and the thermodynamic relationship of the economic system was well laid down by NGR and his research work on the entropy law and the economic process (1971) today finds inroads into many new and emerging fields that aim to address the biophysical and planetary limits to growth (Lovelock,1979, Rockstrom et al, 2009). These well established principles and further research have led to new concepts and approaches which have emerged to reduce the negative environmental impacts due to the economic processes. These include industrial ecology (Frosch and Gallopoulos, 1989), circular economy (Pearce and Turner, 1989), industrial metabolism (Ayers, 1989,1994), cradle to cradle approach (McDonough and Braungart, 2002) and the blue economy (Pauli G, 2010). The Circular Economy (CE) is embedded in an economic system which is governed by the laws of thermodynamics and this marks the shift of the CE approach from the traditional open ended linear system (Pearce and Turner 1986). The concepts of circular economy, degrowth (Kallis, 2011) and steady state (Daly, 1991, Daly, 1994, Czech and Daly, 2004) all have a common thread in that they are a departure from the neoclassical Newtonian viewpoint, and all three are concerned about the source-sink imbalances due to the large amounts of throughput generated by the energy and matter intensive economic processes. While many theoretical, arithmomorphic and metaphoric concepts on entropy-economics relationship were order of the day in the past, and newer ones still emerging, very few works are based on the biophysical real world study of entropy in economic processes. With the focus having shifted from Economic growth alone to development and sustainable development where economic growth is to be balanced and cannot continue at the cost of environmental damage, this thesis attempts to link the entropy law to sustainable development and climate stability concerns of the day. Taking a set of economic activities in a development process (Urbanization case) and the most energy intensive sectors that are the main drivers of climate change like the energy sector, Building sector and AFOLU[8], the Thesis provides a new dimension of analyzing the development process and sustainable development from the entropic lens. This thesis also takes forward the work of NGR much beyond the established entropy and economic process linkage and attempts to bring it at the centre-stage of climate stability and sustainability science research.

8 AFOLU stands for Agriculture, Forest and Other Land Uses.

1.3 Research Questions

1 (a) Is there a relationship between entropy and development process?

(b) What is the relationship between entropy and development process?

2 Can the relationship between entropy and development process be understood from the sustainable development perspective?

1.4 Expected Outcomes

1. To carry forward the work of NGR, through studies of the last 45 years of research, and link entropy to development process and sustainable development. This would contribute to the Ecological Economics school of thought which focuses directly on thermodynamics, sustainability and climate change.

2. Mainstream Entropy in Climate Change and Sustainability debate using case study of city

1.5 Layout of the Thesis

The thesis comprises of six chapters. A brief description of the chapters is given below.

Chapter 1: Chapter 1 deals with setting the research context based on literature review, dwelling upon mainly the development vs climate change dilemma, finding the research gaps and framing the research questions. It also mentions the expected outcomes.

Chapter 2: This Chapter deals with entropy and the economic process focusing on the works of NGR, and carrying the propositions laid by him towards linking development with the Second Law of Thermodynamics. Its an in depth study of the works of NGR from historical perspective to the latest works that show his reemergence. The Chapter provides a theoretical framework for the study.

Chapter 3: This Chapter covers the overall methodology of the research study. The Chapter dwells briefly upon the complexity of choosing the right methodology for the transdisciplinary research, especially in the field of thermodynamics and economics, which is quite challenging. The case study methodology has also been briefly described in the context of understanding and answering the research questions.

Chapter 4: This Chapter addresses the research question on the relationship between entropy and development process and leads to the second question of linkage with sustainable development. This Chapter analyzes the different economic growth, development, sustainable development and thermodynamic linkages emanating out of energy use. The climate change and global sustainability context have also been dealt with. This Chapter helps in providing the basis for formulating the right approach for the case study on urbanization as a case of development.

Chapter 5: This Chapter deals with the Guwahati city case study and the methodologies adopted. The Chapter in Part A describes the case study methodologies in detail for each of the sectors studied, together with datasets and methods used for emission calculations. The Chapter dwells upon detailed energy use and resultant thermal and CO_2 emissions in electricity consumption, fossil fuels, building construction and AFOLU sectors, which are considered as the key drivers of climate change. The resultant waste output of entropy generated and CO_2 emission have been combined together to come up with a single entropy value for the energy input and resultant waste generation. This Chapter also dwells upon the outcome of the research in form of results and analysis of the case study.

Chapter 6: This Chapter briefly sums up the research and dwells upon the answers to the research questions, lists briefly the policy implications and the new contribution of the study in the field of Ecological Economics . It also mentions the limitations of the research.

CHAPTER 2

2 Thermodynamics and the Economic Process: Theoretical Framework

> *The final point is that the earth is a thermodynamic system open only with respect to energy* (NGR, 1975, p356)
>
> *Since the Entropy Law allows no way to cool a continuously heated planet, thermal pollution could prove to be a more crucial obstacle to growth than the finiteness of accessible resources* (NGR, 1975, p358)

2.1 Introduction

This Chapter dwells upon the past and current research focused on understanding the relationship between thermodynamics and economic process through literature review. In doing so this Chapter tries to answer partly the first Research Question: "Is there a relationship between Entropy and the Development process? If it is so then, what is the relationship?" The literature review in this Chapter is focused on the themes of thermodynamic laws, the relationship between economics and thermodynamics with thrust on works of Nicholas Georgescue-Roegen (NGR), biophysical limits to growth and energy use in the economic process, and differences between neoclassical economics (NCE) and ecological economics approach to economic growth and development by bringing in the thermodynamic perspective. The present Chapter dwells upon the foundational aspects of the theories of NGR and ecological economics, and establishes the theoretical framework to move to Chapter 4 which dwells on the thermodynamics and development process relationship and also looks at sustainable development from entropy perspective. Before going onto the theories propounded by Nicholas Georgescue-Roegen (NGR) and exploring the thermodynamics-economics relationship, it is pertinent to give a brief introduction of NGR at the beginning as a tribute to him. This research study is inspired by the life and works of NGR, and would remain incomplete without his brief bio-sketch that would not only provide the required insight in understanding his works which bear great significance today especially in the light of climate change threats and the environmental sustainability of the human economic growth and development, but also would throw light on the future course that this study should take. Therefore, a brief biosketch of NGR is presented below.

2.2 A Brief Biosketch: Life and Works of NGR – Acceptance, Neglect & Reemergence

Nicholas Georgescue-Roegen, born on 4th February 1906 at Constanta, Romania, obtained a doctoral degree in mathematical statistics and conducted post doctoral study with Karl Pearson[9], in London. Thereafter, he moved to USA. In 1934, at Harvard he met Joseph Schumpeter (1883-1950), whose influence turned Georgesue-Roegen from a statistician to an economist. His colleagues included Wassily Leontiff, Edgar Hoover, Nicholas Tintner and Paul Sweezy among others. In 1937, despite having got an offer of faculty position at Harvard, NGR returned back to Romania where for 12 years he practiced his knowledge in mathematics, statistics and economics by applying them to everyday situations in life (Gowdy & Mayumi, 1999). He returned to the United States in 1948, and in 1949 joined as a faculty of Economics at Vanderbilt University in Nashville, Tennessee, and retired in the year 1976. He died on 30th October 1994 at Nashville, Tennessee. His journey from statistics, mathematics, economics to revolutionary/evolutionary economics saw him moving from a state of great appreciation to criticism. In the words of Paul A Samuelson, "Prophet of a new and revolutionary economics methodology", one who "is so far ahead of his times" and "… he fails to get the recognition he deserves" (Samuelson, 1999). Once Samuelson even called him "a scholar's scholar, an

9 Karl Pearson (1857-1936), the noted English mathematician who is credited with establishing modern Statistics

economist's economist", but in his later works ignored NGR totally. According to Daly, "Some of his later works were received with deafening silence, namely the relationship between economics and thermodynamics (Daly, 1999). However, Mark Blaug (1985) included him in his book Great Economists since Keynes. NGRs numerous contribution to economics have been grouped into two categories: the normal science and the revolutionary science. The normal science being his contributions to fundamental work in utility theory, consumer choice, production theory, and input–output analysis. Revolutionary science being referred to mainly his work on *The Entropy Law and Economic Process* (Daly, 1996).

From 1950 to 1966, NGR contributed to mathematical economics and gave an extraordinary epistemological criticism of neoclassical theory, which culminated in publication of Analytical Economics in 1966. This work was well received with many reviews in journals including the American Economic Review and the Economic Journal. The year 1966 marks the beginning of his second phase of thought which was devoted to research on economic institutions of agrarian societies and theory of production. During this period he revised the neoclassical theory of production, and gave the distinction between funds and flows[10]. The funds-flows model became central to the entropy theme and resulted in the fundamental bioeconomic text - The Entropy Law and the Economic Process in 1971, along with additions of value theory (Bonaiuti, 2011). NGR observes in Chapter X: "Entropy, Value and Development" of the magnum opus, "*our whole economic life feeds on low entropy...Low entropy, as I have stated earlier, is a necessary condition for a thing to have value*". He goes further to say "*… the true product of the economic*

10 Fund (also called Fund Service Resource) is that part of production process which does not change during the production process, has the property of economic invariableness, but rather may suffer wear and tear, and cannot be stockpiled. It provides service at a fixed rate. On the other hand Flow (also called Stock Flow Service) is the which gets transformed materially during the production process, essentially raw materials. Flow resources are used up in the production process, and can be stockpiled, and can be used at any desired rate (Daley & Farley, 2004). In the words of NGR, "The funds – land, capital proper, and the entire population – go into the process and come out of it intact" & "There are only two flows: an input flow of low entropy and an output flow of high entropy i.e. of waste" (NGR, 1971 p283-284). Contrary to Fund-flow model of NGR,the classical economists von Newmann & Sraffa adopt flow-flow approach in which old machines at the end of the production cycle are treated differently than those that entered at the beginning of the production cycle (Kurz & Salvadori, 2003)

process is not a material flow, but a psychic flux – the enjoyment of life by every member of the population". According to NGR, enjoyment of life[11] has an intensity at each instant of time, but it cannot accumulate in a stock. NGR also dwelt upon development and opined that a country must plan its development not beyond the "*natural resources within its own territory*". He broke down economic development into two elements: development proper and pure growth. However, he concluded, "*even with constant population and a constant flow per capita of mined resources, mankind's dowry will ultimately be exhausted if the career of the human species is not brought to an end earlier by other factors*" (NGR, 1971).

Maneschi & Zamagni (1997) term the magnum opus as "challenging book" and the "most complete expression of NGR's scientific thought". The appearance of the Entropy Law and the Economic Process was followed shortly by the Limits to Growth by the Club of Rome (Meadows et al, 1972) - both stressed upon the dangers of economic growth and drew negative reactions from mainstream economists. Due to the language complexity, the work of NGR caused, however, much less of a stir than the Limits to Growth (Bonaiuti, 2011). Initially NGR and the Club of Rome developed strategies of mutual support, and were viewed as natural allies with NGR becoming a member of the Club of Rome, and Dennis Meadows acknowledged the influence of NGR on the Club. However, as the Club of Rome brought out a series of reports (1972-1980), each drifting away from the first Report's concern, the gap widened between adamant defense of degrowth by NGR, and the Club of Rome's less firm view of "sustainable growth", leading to the self-isolation of NGR (Levallois, 2010). For many long years, there was no debate, whatsoever, about the bioeconomics proposed by NGR either in theoretical or empirical aspects (Bonaiuti, 2011). NGR was a possible candidate for the Nobel Prize in economics, but the fact that he never received the prize could be partly due to the unorthodox

11 If e stands for enjoyment of life, e=Consumption Enjoyment + leisure Enjoyment – Work Drudgery (NGR, 1971, p285)

ideas he displayed which set him on a collision course with the neoclassical establishment whom he referred to as 'standard economists' and which included several Nobel laureates too, and he would "use them occasionally as whipping boys to illustrate" their erroneous ways of thinking (Maneschi & Zamagni, 1997).

NGR was founder of a school of thought rather than the adherent of any existing school. He was an autodidact, complex and sceptical, and never hesitated to point out shortcomings of others though he drew his world view much from the past and present thinkers and scholars. He criticized Marx and his followers for viewing natural resources as a free gift of nature. While he singled out Jevons as the archetype of the mechanistic dogma, he fully excused him in the *Coal Question* for ignoring the Entropy Law as the law itself was formulated by Clausius the very year Jevons' book went to print (NGR, 1971, p296, Maneschi & Zamagni, 1997). He termed the statistical thermodynamics theory of Ludwig Boltzmann as an idiosyncrasy, and went on to state, "*.. a pile of ashes may very well become capable of heating the boiler. Also, a corpse may resuscitate to lead a second life in exactly the reversed order of the first. Only, the probabilities of such events are fantastically small. If we have not yet witnessed such "miracles" the advocates of statistical mechanics contend it is only because we have not been watching a sufficiently large number of piles of ashes or corpses*" (NGR, 1971, p7). NGR also gave an elaborate treatment to Shannon's Information Entropy and concluded that Shanon's "information" is not information in the usual sense and hence appending the word entropy to information was done only to gain "external luster", and that there is "danger" in such scientific terminology (NGR, 1971 p405-6). NGR was critical of Costanza's energy theory of value[12], as

12 Energy Theory of Value: Proposed by ecologists and physicists to complement / replace the standard neoclassical theory of subjective utility-based value. It is based on thermodynamic principles in which solar energy is recognized to be the only primary input to the global ecosystem, as earth is a closed system and it receives only solar energy as input. It says that at the global scale free or available energy from the sun (and the past solar energy stored as fossil fuels and residual heat from the earth's core) are the only primary inputs to the system. Labor, manufactured capital, and natural capital are intermediate inputs to the economy. Studies have shown very close relationship between available energy consumption and economic output (Costanza, 2004)

well as the emergy[13] concept of H.T. Odum (Martinez-Alier, 2013). NGR was also a forceful critic of steady state[14] and sustainable development, but defended degrowth[15] or even agrowth[16]. He insisted that even a non-growing steady state economy is an impossible goal (Bonaiuti, 2011, Gowdy, 2015). NGR even refused to be drawn into ISEE[17], and he preferred the word "Bioeconomics" to "Ecological Economics" (Martinez-Alier & Muradian, 2015). Talking of the ISEE and sustainable development in one breath, NGR wrote in a letter to Kozo Mayumi in 1992 "Actually the capital sin of that International Association is that with an overabundant funding they market the most dangerous snake oil of all time, sustainable development" (Bonaiuti, 2011). Herman Daly (1996) in his obituary essay on NGR wrote, "… *I was saddened that his latter*

13 Emergy: It is defined "available solar energy used up directly and indirectly to make a service or product" (Odum, 1996, p. 8). It is a measure of energy used in the past and thus is different from a measure of energy. Its unit is emjoules or seJ or sej (sun equivalent Joule or solar emjoules). Empower is emergy per unit time. It was suggested to be used for value and sustainability assessment. Total annual emergy contributions to global processes (not non renewable) is 15.83 E24 sej/yr of which 3.93 sej/yr is from solar insolation, 8.06 sej/yr is from deep earth heat due to radioactivity etc., & tidal emergy 3.84 sej/yr. On the other hand, the non-renewable emergy is 88.8 sej/yr. Net enmegy means emergy of resources delivered by a process minus the emergy invested therein. (Odum, 1996, 1998, Brown & Ulgiati, 2004, 2011, IISD, 2010)

14 Steady State in the Classical view means an economy in which stocks of physical wealth (capital) and people (population) are held constant. Capital is not static but continuously renewed by depreciation and replacement The accumulation of physical wealth is controlled by controlling energy & matter use. Population is held constant by some form of birth control practice (and not by high death rate). The view was first propounded by Mill, and with some modification revived by Keynes as "quasi stationary community". Daly (1993) defines it as an economy "whose scale (that is, resource throughput, equal to population times per capita resource use) remains constant at a level that neither depletes the environment beyond its regenerative capacity nor pollutes it beyond its absorptive capacity. Such an economy adapts and improves in knowledge, organization, technical efficiency, and wisdom; and it does this without assimilating or accreting an ever greater percentage of the matter-energy of the ecosystem into itself, but rather stops at a scale at which the remaining ecosystem (the environment) can continue to function and renew itself year after year. The non growing economy is not static-it is being continually maintained and renewed as a steady-state subsystem in dynamic equilibrium with its environment" (Daly, 1993, 2007). Steady state economy is stable against fluctuations, protected by opposing gradients (Annila & Salthe, 2009).

15 Degrowth: Used for the first time in France in 1972 as "Decroissance", degrowth means primarily -ve GDP growth. It also means reduction in consumption levels, or physical degrowth meaning reduction in the size of economy by resource use and emissions (van der Bergh, 2011). NGR said, "even at zero growth, the continued consumption of scarce resources will inevitably result in exhausting them completely" (Gorz, 1980 p13)

16 Agrowth is proposed as indifference to economic growth (increasing GDP). It is seen as better suited to find democratic support than degrowth, and go for effective environmental and complementary policies instead. NGR's bioeconomic dream appears to be closer to agrowth rather than degrowth (van der Bergh, 2011, 2012, Missemer, 2016)

17 ISEE: International Society for Ecological Economics set up in 1988 at Louisiana, US under the Chairmanship of Robert Costanza. It publishes the Journal Ecological Economics since February, 1989. The first Chief Editor was Robert Costanza with Herman Daly, Ann-Mari Jansson, and David Pearce as the Associate Editors (Costanza, 2003). The first article in the journal was "What is Ecological Economics" by Costanza, p1-7 (Costanza, 1989).

years were so marked by bitterness and withdrawal, brought on in part by the failure of the profession to give his work the recognition that it truly merited, and in part by his own irascible and generally demanding personality. So great was his bitterness that he even cut relations with those who most valued his contributions."

Forty six years have elapsed since publication of the Entropy Law and the Economic Process, of which the first twenty years were marked with little or no debates until Khalil started the debate in 1989. In defense of NGR's approach, joined Lozada, Ulgiati, Ayres, Daly. This initial debate, however, confirmed that the Entropy Law was applicable to economic processes and that this stand point would not be seriously questioned in later literature. The issue remains at hand as to how to put to use the 2nd Law of Thermodynamics as an effective tool that could be capable of characterizing the relationship between economics and ecology (Bonaiuti, 2011). After a gap of almost forty years, the Bioeconomics[18] as proposed by NGR with an interplay of thermodynamics and biology based on the Loktian exosomatic evolution and mankind's survival and a "*bioeconomic program for softening the inevitable ecological calamities that would make the survival of the human species the shortest of all on this globe*" is now gaining ground (Missemer, 2016, Bobulescu, 2015, Bonaiuti, 2011). The bioeconomics thesis of NGR, for which he "*devoted all ... research effort over the past twenty years*", but sadly his struggle "*has remained without any substantial influence on the noisy agitation growing around the problem of natural resources ever since the writing on the wall by the oil embargo of 1973/74*", has now been the subject of revival studies for a few years in ecological economics, environmental economics and history of economic thought (Bobulescu 2012, 2015, Missemer, 2016, Farrell and Mayumi 2009, Glucina & Mayumi, 2010, Bonaiuti 2011, Fisk 2011, Hermann-Pillath 2011, Martinez-Alier, 2013, Cleveland and Morris 2014, Henrique & Romeiro, 2015, Martinez-Alier &

18 A word coined by Jiri Zaman of Czechoslovakian Academy and NGR "thoroughly welcomed it" (Bonaiuti, 2011)

Muradian, 2015, D'Alisa, Demaria & Kallis, 2015, Costanza et al, 2016, Lozada, 2017). Glucina & Mayumi (2010) in their review conclude that thermodynamics is very relevant for energy security and climate stability today. The reemergence of NGR can be attributed to the current global warming and climate change scenario coupled with resource scarcity. Today the words of NGR sound prophetic in many respects and also because his voice, as one of the fathers of ecological economics has remained a cry in the wilderness (Missemer, 2016, Bonaiuti, 2011). From the study of the life and works of NGR, it is seen that his theory on entropy law and economic process holds good, and has relevance in the current scenario where human economic activity has led to unprecedented anthropomorphic release of waste (CO_2) and waste heat into the atmosphere leading to the present day insurmountable challenges of keeping the mean global surface temperature rise below 2^0 C[19]. As stated earlier, the present Thesis is inspired by NGR and aims to take forward the thermodynamics and economics relationship in the context of development process. In order to do so, the conceptual and theoretical framework for the present study has been developed which is presented in the sections below.

PART A: CONCEPTUAL FRAMEWORK

2.3 An Enquiry into the Origins of Thermodynamics – Economics Linkage

Biophysical economics or Bioeconomics drew heavily from the seminal works of Charles Darwin, Thomas Malthus, Alfred Marshall, NGR and Frederick Soddy, Kenneth Boulding, Seregi Podilinsky, Robert Costanza, Robert Ayres, Proops, Martinez-Alier, Cleveland among others. A brief history of ecological economics is sketched here primarily based on Cutler J. Cleveland (1999). However, its history can be traced to Francois Quesnay, Mirabeau and Dupont, in 1750, who argued that economic process was subject to laws of nature that operated independently of the human free will. The German chemist Ostwald in 1907 incorporated

19 See Chapter 1 (Para 1.1.1 to 1.1.4)

thermodynamics into the general theory of economic development, and he argued that as human civilization progressed, more and more energy was transformed with ever increasing efficiency. Podilinsky concluded that limits to economic growth lay in physical and ecological laws. Thereafter the early 20th century saw emergence of Frederick Soddy (1877-1956), an English Physical Chemist and a Nobel laureate in chemistry, who maintained that biophysical principles lay at the root of economic wealth creation, and that money could not grow at compound interest rates as thermodynamic laws clearly prohibit that. His theories on the relation between energy, wealth, economics, and thermodynamics were expressed in his 1926 book *Wealth, Virtual Wealth and Debt.* Thermodynamics governs all physical activity in the world, and the laws of thermodynamics govern wealth and poverty. At the same time as Soddy, Alfred Lotka, who was a mathematical biologist, argued that the mechanisms of natural selection could be explained in energy terms; and survival of species was governed by the laws of thermodynamics. Dutch-born economist Tjalling Koopmans (1910-1986), the 1975 Nobel Award winner in Economics, wrote from 1951 onward about limited natural resources and the irreversible nature of the economic process. In 1955, Cottrell, a sociologist, in his book Energy and Society emphasized the role of energy in human affairs. In 1956, Hubbert, a geophysicist by profession, made a startling prediction that the fossil fuel era was short-lived. By this time the energy perspective of economy was gaining prominence. In 1972 the Club of Rome[20] came up with a theory on limits to growth

20 Limits to Growth by Meadows & Meadows (1972) predicted that the world economy was moving towards an era of limits. The emergence of the anti growth school can be traced to Malthus in early 1800s. The Limits to Growth carried forward the premises of Malthus and Recardo by raising questions of induced population growth and diminishing returns to labour and fixed land. Many termed it as an enormous over-simplification of the reality. However, it was not taken too kindly by the NCE, and seen as intrusion by systems analysts, who ran a computer model called World3, into the realm of economists. The level of per capita income sustainable according to the authors was about half of the US GDP in 1970, i.e. 12500 US$ (at 2000 prices) and the world population should stabilize at 4 billion. Beyond this, the world economy would run into environmental problems (Common & Stagl, 2005). Three of the four original authors came up with Beyond the Limits in 1992 (Meadows et al, 1992). However, they concluded that their original conclusions were still valid. This notwithstanding, the NCE advanced the argument in 1990s that economic growth is good for environment by inventing the Environmental Kutznets Curve (EKC). The EKC hypothesis in short is that as economic growth proceeds, environmental damage increases first, then it levels off, and later it declines (Common & Stagl, 2005, Stern, 2004)

re-emphasizing role of energy in economy. Almost the at the same time, as the Club of Rome, H.T Odum carried forward the natural selection theories of Darwin and Lotka and gave a general energy law that stated that natural selection was maximization of useful work obtained from conversion of energy. Odum also argued that wherever a monetary flow existed in economy, there would be energy flow in the opposite direction. Costanza carried forward the ideas of Odum, who coined the word "embodied energy" to describe the total energy cost of a given goods or services (Costanza, 1980).

Robert Ayres, a physicist, applied thermodynamic laws to economic processes using a material energy balance model and exergy analysis for the first time in 1969. He argued that exergy[21] is a property of all energy and matter and can be used to measure input natural resources as well as wastes (Ayres & Kneese, 1969, Ayres, 1978, Ayres, 1996). Daly (1974) criticized the circular flow model of the economists and proposed a steady state economy in which the stocks of physical wealth, called capital, and populations are held constant. He believed that such a transition is inevitable due to rising world population, depletion of resources and degradation of the environment. Though such a long genesis spanning over two centuries is described above, the foundation of the new trans-disciplinary science called Ecological Economics took place only by 1988 when the International Society of Ecological Economics (ISEE) was founded under the Chairmanship of Robert Costanza and the first Journal of Ecological Economics was brought forth in 1989. For Ecological Economics the study of economy–environment interdependence is foundational (Common & Stagl, 2005). To grow and develop, the economy necessarily 'feeds' on sources of high-quality energy matter first produced by nature. This tends to create disorder in the eco-sphere (Rees 2003). Limitations to growth are imposed from source as well as sink side (Daly, 1994, Daly & Farley J, 2007). ***Lack of energy may stop economic growth, but assuming***

21 See Foot Note 24

that new sources of energy are innovated fast enough, still the problems of high entropy, waste and pollution would persist (Faber et al, 1995).

The discussion above establishes in no unclear terms that there is a history of almost two centuries and a large number of economists, scientists and scholars in the past have very seriously dwelt upon the thermodynamic basis of all economic activities, and, therefore, the relationship of thermodynamics with economics cannot be dismissed as merely metaphoric or analogous. If so, then how thermodynamic epistemology impacts the economic thought?

2.4 Mechanistic vs Thermodynamic Epistemology in Economic Thought

The NCE[22] economic thought was broadly derived from the mechanistic epistemology of Classical mechanics as developed by Newton and Leibniz. The relationship between NCE and natural science, thus, is the urge to be deterministic and predictive. The early co-development of economics and natural sciences started with great strides made by the classical mechanics and new scientific discoveries based on the Newtonian principles. For example discovery of the planet Neptune by laws of motion, prompted W.S. Jevons to say "*... if economics is to be a science at all, it must be set up as a mechanics of utility and self-interest*" (Mayumi & Gowdy, 1999). Slowly the Newtonian world view became the dominant academic paradigm (Constanza et al, 2008). In NCE all processes are fully reversible, and equations and models used to describe the system are time symmetric. The standard economics follows the circular flow[23], in which the economic process apparently acts as a perpetual motion machine (PMM) requiring no fresh inputs of energy and matter and producing no waste contradicting the Entropy Law (Daly &

22 The word "Neoclassical Economics" was coined by Thorstein Veblen in 1900 who used the terminology to characterize economists who adopt classical method of causal deduction from natural laws, and he termed the works of Alfred Marshall as the best which drew upon the classical method as propounded by Newton and Leibniz (Martins, 2016).

23 Circular Flow: Economy has two parts- the production unit (firms) and consumption unit (households). Firms produce and supply gods and services to households, while the consumer side demands goods and services from the firms making a demand supply loop. Prices are determined by interaction of supply and demand (Daly & Farley, 2004)

Farley, 2007). In reality, there is no such PMM and a real world economic process is subject to the thermodynamic laws and one needs to address environmental concerns, global warming and climate change issues arising out of the use of energy and matter in the process. According to Mirowski (1989), the early neoclassical economists created their revolution, motivated by the desire to achieve the status and prestige of the physical sciences, by substituting utility for energy in the physics of their day. On the other hand the roots of the EE go deep into the sciences of Thermodynamics (especially the Entropy Law), Ecology and Evolution as well as the General Systems Theory. The relationship of EE and the natural sciences is through a series of inter-connects that touch upon ecology, environment, evolution, development, climate change and sustainable development on one hand to new paradigms of economic growth, issues of source and sink, efficiency, ecosystem services and issues of energy and matter, making EE non predictive and non deterministic, in short unlike classical mechanics. Economies are open complex adaptive systems which are far from thermodynamic equilibrium. Economies are also complex in nature, hierarchically nested and show adaptive and evolutionary behaviour (Ramos-Martin & Proops, 2001).

The classical mechanics versus thermodynamic basis of the above differences between NCE and EE is to be understood by comparing fundamentally a thermodynamic system and a classical Newtonian system. The subject matter of classical mechanics pertains to point particles and rigid bodies, which are fictitious model systems non-existent in nature. For example, a point particle does not have rotational or vibrational motion, and hence cannot store energy within it. On the other hand real atoms stores energy internally and can vary the amount by absorption and/or emission of radiation. Similarly, the atoms of a rigid body, being point-like and fixed in a rigid lattice cannot vary their energy either by absorption or emission. The rigid body and point object models are useful for approximating the behavior of real world when changes in internal energy are negligible. On the contrary, thermodynamics systems are real world objects having internal degrees of freedom, and thus can store internal energy by way of numerous translational, rotational and vibrational modes. A hypothetical rigid body has zero internal energy (U=0), while a thermodynamic system has an internal energy U>0. It is the existence of internal energy that can be varied makes a system thermodynamic (Leff, 2012). Thus, it follows ipso facto from the above argument that real world economic systems that work upon real energy and matter ought to be thermodynamic systems. Hence, the laws of thermodynamics would necessarily apply on them. Thus, it is established that economic processes are thermodynamic in nature which implies that in any economic process energy matter would be conserved, and at the end of the process cycle, entropic waste would be generated, however small it may be, depending upon the efficiency of the economic process. While there may be questions as to how thermodynamic laws need to be incorporated into the economic theory (Glucina & Mayumi, 2010), but there cannot be a doubt that it would need to be applied to an economic process as regards energy and matter interactions are concerned.

2.5 NCE Growth Models & Production Function- The Thermodynamic View Point

According to NGR, the conventional economic growth models were reversible and capable of replication since they were based on the mechanistic dogma of Classical mechanics. In his own words, “The intriguing ease with which Neoclassical economists left natural resources out of their own representation of the economics process may not be unrelated to Marx's dogma that everything nature offers us is gratis. ... The absence of any difficulty in securing raw materials by those countries where modern Economics grew and flourished was yet another reason for economist to remain blind to this crucial economic factor” (NGR, 1971). NGR believed that economic growth models which did not take into account resource and energy explicitly should not be taken seriously (Miernyk, 1999). According to NGR, conventional economic analysis confused both funds and flows which led to the misinterpretation of the relation between manufactured and natural capital. The NCE theory of production is based on an aggregate function of production as given below:

$$Q = A\,f\,(K, L, R) \quad (2.1)$$

where production Q increases with growth of capital stock (K), labour (L) and technological progress A, while reducing the natural resources (R). This means any quantity Q_0 of a product can be produced reducing R as long as capital stock is increased sufficiently. This implies that natural resources and man-made capital can fully substitute each other. An example oft quoted in the literature is of making a bigger pizza by reducing the amount of flour simply by using a technology that is more advanced oven or employing two cooks instead of one. This approach does not conform to the 1st Law of Thermodynamics i.e. the law of conservation of energy and matter (Daly & Farley, 2004, Bonaiuti, 2011). The flow of input matter that enters the production process must be equal to the output matter i.e. the goods produced and waste. (Bonaiuti, 2011). This statement can be conveniently represented through the equation below, which incorporates both the laws of thermodynamics:

$$M_{input} = M_{output} + \Delta M \quad (2.2)$$

where M_{input} is the input matter into the production process, M_{output} is the goods produced ΔM which is the entropic waste.

Another criticism of the NCE production function is non inclusion of energy as a factor of production (Glucina & Mayumi, 2010, Baumgartner et el, 2004, Kummel, 1989, Ayres 1998). Then, If energy were to be considered as a part of the production process, the energy conservation law would hold good, and on lines of Eq No. 2.2, one can write

$$E_{input} = E_{output} + \Delta E \quad (2.3)$$

where E_{input} is the input energy into the production process, E_{output} is the energy consumed for the goods produced (M_{output}), and ΔE is the entropic waste energy or waste heat. Assuming that ΔM & ΔE cannot be recycled 100% in an economic process, and thus would accumulate at the end of every process cycle, in the biosphere as harmful waste causing phenomenon such as global warming and climate change (or even ozone hole, or cause various types of cancers!), and due to low efficiencies of the economic processes (this Thesis attempts to arrive at efficiency of resource use in the case of urbanization as a development process! See Chapter 5, Section 5.7), the waste would also necessarily cause resource scarcity (E_{input} & M_{input}). However, resource scarcity beyond ΔM+ΔE cannot be attributed to thermodynamics (except that the low entropy resources are products of some other natural processes which are also thermodynamic, and hence entropic). This brings the argument to scarcity and waste, which have been discussed briefly in the paragraphs below.

Notion of Scarcity: The biggest criticism of the NCE production function is the non accounting for the increase in degradation of natural resources from the ecosystem. Robert Solow had stated that "there is in principle no problem. The world can in effect get along without natural resources" (Daly & Farley, 2004, Bonaiuti, 2011). This brings us to the issue of scarcity and substitution. NCE talk only of relative scarcity- "a good is scarce in relation to other scarce goods" and of substitutability - "people are willing to give up something else in order to obtain one additional unit of a scarce good rests on the implicit assumption that people consider these two goods to be substitutes" (Baumgartner, 2002). NGR defines scarcity in terms of entropy as a "given amount of low entropy" that "can be used by us only once" (NGR, 1971). NGR argued that unlimited substitution would work only with an unlimited supply of low cost energy as the Entropy Law does not permit perpetual growth (Miernyk, 1999). The basic differences between NCE environmental and resource economics and EE is whether the environmental goods and services are viewed as relatively scarce or as absolutely scarce. The belief held by ecological economists is that many environmental goods and services are not only scarce in a relative sense, but also in an absolute sense. The First and the Second Laws of Thermodynamics need to be combined in the study of how natural resources are extracted, used in production, and give rise to emissions and waste, thus leading to integrated models of ecological-economic systems (Baumgartner, 2002). The question of scarcity also brings to fore the scarcity of matter for which NGR proposed the 4^{th} Law of Thermodynamics which states that perfect recycling is 'categorically impossible', whence matter becomes dissipated and unavailable for human use in the same way that the second law prescribes for energy. He proposed that matter is entropic and matter scarcity may eventually arise. Running a car forever on recycled fuel is a perpetual motion machine of the second kind which is denied by the 2^{nd} Law (Lozada, 1999). However, the universal acceptability of the law is limited, and it has been theoretically refuted. Nevertheless, almost all accept that materials can never be recycled with 100% efficiency because there are always entropic losses, and tremendous increase in the entropy of the environment (Ayres, 1999, Bianciardi, Tiezzi & Ulgiati, 1993, Schwartzman, 2008, Hammond & Winnett, 2009). While matter can be converted into energy, energy cannot be converted into matter in the real world economic process. If this was so then the abundant solar energy could be used to solve all growth problems. The mass energy equivalence is given by the Einstein's famous equation

$$E = MC^2 \tag{2.4}$$

But practically in the present world at the given level of knowledge and technology, conversion of energy to matter is not possible except in nuclear accelerators and that too very momentarily. Assuming that there were such an economic process to convert energy to matter, then, out of the ~20,000 EJ of energy that humanity has consumed from the industrial revolution till date, only 220 tons of matter (and we could probably choose it to be coal or oil) would come out assuming an 100% efficient process. Looking at the other way round, the highly inefficient human economy wasted billions of tons of precious fuels in past 300 years, whereas just about 250 tons would have sufficed with little or no emissions. This brings us to ask (Nordhaus 1973) if there are enough energy resources to run the world economy indefinitely, which depends on whether certain future technologies would actually become available in future and secondly what would be the the price for the energy availability in future.

Pollution and Waste: NGR emphatically stresses that pollution is brought to fore by the Entropy Law. He says "… *product of the economic process is waste, waste is an inevitable result of that process and ceteris paribus increases in greater proportion than the intensity of economic activity*" (NGR, 1971). Robert Ayres et al (1996) argued that thermodynamics offered a unique way of accounting for resources and wastes. According to most economists, consequences of producing and disposing of waste are not internalised in market prices, and thus occurrence of waste is due to market failure (Baumgartner 2002). Though waste can be partly attributed to failure of the market mechanism, from thermodynamic view point it is an unavoidable consequence of industrial production. Economic activity consists of three different processes namely production, consumption and reduction. In production low entropy energy is employed to convert raw materials and natural resources into consumption goods. The goods are consumed by the consumers to increase their welfare and well being, and after consumption, what is left of the goods is waste. Modern industrial economies work upon these waste to reduce it by recycling, reusing or transforming into other useful goods that are input to some other production processes. This is called reduction. Material flows in the economy are not in closed cycles, as is the case in ecosystems, but rather as large through puts through the economic system. Materials are taken from large reservoirs outside the economic system which not only emits waste heat, as do the ecosystems, but also generate large quantities of material waste (Baumgartner, 2002).

2.6 Entropy and Economic Process: Summing up the Conceptual Framework

Taking the analogy of coal that is burnt to drive a locomotive engine from one station to another, NGR says that the process of coal getting transformed into ashes is as per the dictate of the First Law of Thermodynamics, which is the law of conservation of matter and energy which is "not in contradiction with any of the laws of mechanics". NGR argues that at the beginning, the chemical energy of coal is free and available for producing some mechanical work, but in the process, the free energy loses this quality of producing work, ultimately dissipating into bound energy i.e. energy which cannot be used for the same purpose. Thereafter, NGR goes to define entropy as "an index of the relative amount of bound energy in an isolated structure" or more precisely as "how evenly the energy is distributed in such a structure". NGR calls high entropy "a structure in which most or all energy is bound", and low entropy "a structure in which the opposite is true". NGR, thereafter, dwells upon the direction of flow of heat and says "*The common fact that heat always flows by itself from the hotter to the colder body, never in reverse, came to be generalized as the Entropy Law, which is the Second Law of Thermodynamics and which is in contradiction with the principles of Classical mechanics*". NGR also stresses that the entropic degradation goes on by itself regardless of whether or not the free energy is used to produce mechanical work (NGR, 1971). There is almost unanimity that the laws of thermodynamics have relevance to economics, but the manner and extent of their application and to what extent does the entropy law, in particular, impose limits on economic growth are still matters of debate. Much has been written on this question, well summarized in literature (Ruth, 1993, Cleveland and Ruth, 1997, Sollner 1997, Raine, Foster & Potts, 2006, Annila & Salthe, 2009, Hammond & Winnett, 2009, Glucina & Mayumi, 2010, Bonaiuti, 2011). As long as energy is used, ***entropy will continue to increase*** as energy has two components always:

$$\text{Energy} = \text{Exergy}^{24} + \text{Entropy} = \text{Available energy} + \text{unavailable energy} \quad (2.5)$$

The review of literature and discussion as put forth above has helped in understanding the Thermodynamic basis of the economic process and in drawing and filtering out the key concepts that are important for the Study which include application of the 1st and 2nd laws of thermodynamics, efficiencies of energy and matter use in a process, scarcity of resources (impact of production on source), production of waste and waste heat (impact of production on sinks). Based on these concepts, a Theoretical Framework has been proposed in Part B of this Chapter.

PART B: THEORETICAL FRAMEWORK

2.7 Theoretical Framework of the Study

The conceptual framework of the Study has been discussed at some length in Part A of this Chapter, stressing on the energy matter input to economy and application of the thermodynamics laws that are at the core of our understanding of the global warming and climate change threats to human survival through resource scarcity and waste assimilation challenges. *The present Study examines, through a case study methodology, the linkage between energy matter input and waste generation through the lens of entropy*[25] *by proposing to combine waste heat and* CO_2 *emission in an economic process*. In the paragraphs that follow, the constructs used in the Study

24 Exergy: A system delivers the maximum possible work as it undergoes a reversible process from the specified initial state to the state of the its environment i.e. the dead state- this represents the useful work potential of the system at the specified state and is called exergy. (A system is said to be in dead state when it is in thermodynamic equilibrium with the environment it is in). Exergy represents the upper limit on the amount of work that can be delivered by the system without violating any thermodynamic laws (Cengel & Boles, 2011). All fossil fuels are 100% exergy, and exergy content can be equated to electric power output (Ayres, van der Bergh, 2000)

25 The Entropy Law is applicable on all economic processes where energy and matter goes in as input. Hence, the research study has made an attempt to show application of the laws of thermodynamics in real world process. However, in doing so, there are difficulties and hurdles. Entropy treatment is considered a difficult proposition. There was no entropy meter (NGR, 1971, Ayres, 1996). Entropy is difficult to grasp as it is essentially non observable and that there is no straight cookbook kind of formulae to calculate absolute entropies of systems, other than calculating differences in entropy (Ayres, 1996). Baumgartner (2003) argues that entropy is difficult and "is a very abstract concept and it is notoriously difficult to apply in specific contexts". According to Mayumi & Glucina (2010), since the physical quantities introduced by the 1st Law (*Internal energy*) and the 2nd Law (*Entropy*) of Thermodynamics cannot be experienced directly, it contributes to the confusion about their application.

based on the principles of thermodynamics and the economic process/ development process have been given.

2.7.1 Thermodynamics in Real World Economics- Adopting Systems Approach

According to NGR the economic process is non linear and irreversible following the arrow of time. The economic process cannot be treated as a perpetual motion machine rather it is a process which requires energy matter inputs that get degraded during the course of production. The best representation of the economic process is the systems perspective which is non linear and irreversible.

Systems Approach: System is a part of the world in which we have a special interest, and the surroundings comprise of the region outside the system where measurements are made (Atkins & Paula, 2010). A system is defined as a quantity of matter or region in space chosen for study (Cengel & Boles, 2011). A system is an arbitrary geometric portion of the universe with fixed or movable boundaries and may contain matter, energy or both (Peixoto & Oort, 1992). The Universe is a hierarchy of systems; that is, simple systems are synthesized into more complex systems from subatomic particles to civilizations. All systems, or forms of organization, have some characteristics in common, and it is assumed that statements concerning these characteristics are universally applicable generalizations (Bowler, 1981). A system is characterized by system variables, extensive and intensive, that describe the system, and state and path functions (Atkins & Paula, 2010). The product of a pair of intensive and extensive variables of a system have dimensions of energy (Peixoto & Oort, 1992, p11). The inner working details of the system are not required to be known, as long as the macroscopic properties of the system are known (Glucina & Mayumi, 2010). Systems can be open[26] closed[27] and isolated[28].

26 When a thermodynamic system exchanges energy and matter with the surroundings, it is termed as open system
27 When the system exchanges only energy from the surroundings, it is termed closed system.
28 When neither energy nor matter is exchanged between the system and surroundings, the system is said to be isolated. An isolated system is ideally the entire universe

Most natural systems such as atmosphere, oceans, biosphere and ecosystems are open systems exchanging matter and energy with surroundings (Atkins & Paula, 2010). Open systems are sustained by a continuous supply and removal of matter and energy. Open systems can be classified into three categories namely decaying[29], cyclic[30] and fluctuating[31]. Open systems could also be cascading[32] in nature (Peixoto & Oort, 1992)

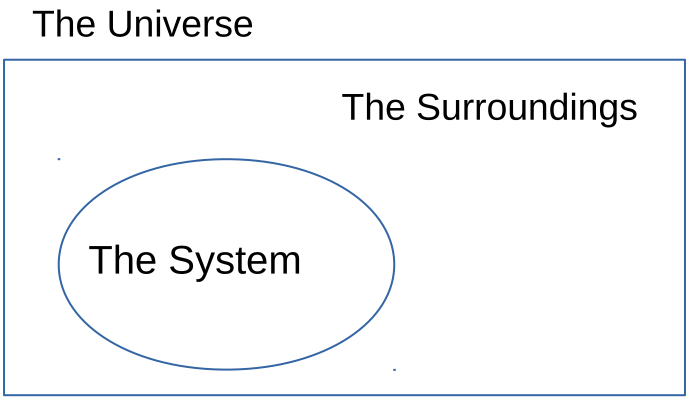

Fig. No. 2.1: System and Surrounding Relationship

Process, Economic & Development Process: Any change a system undergoes from one state (defined by a set of values of the system variables) to another (defined by another set of values of the system variables) is called a process, and the system may perform useful work (say achieve motion against an opposing force), or work may be done upon the system (Cengel & Boles, 2008). The set of actions and operations that are involved in production of goods and services may be called an economic process. Each such process may consist of one or many elementary processes (NGR, 1971, p235). Each of the elementary process would belong to one of the three classes namely physical, chemical or biological. The economic process, and in turn each of the elementary process contained in it, is sustained by a flow of low entropy (high quality) energy, materials, and ecological services from the environment.

29 Decaying or dissipative systems consume their own mass or energy or both. An example would be river runoff during dry season

30 Cyclic systems follow regular oscillatory behaviour. Gulf stream could be an example of a cyclic system

31 Randomly fluctuating systems change in an irregular way with unpredictable variations in the variables. An example could be a turbulent whirlwind in the atmosphere

32 A cascading system is a chain of open sub systems which are dynamically linked by a cascade of matter and energy so that output of mass or energy from one sub-system becomes the input for the next subsystem

Growth & Development: Development differs from growth in the sense that the former is qualitative and the later is quantitative. An economy can develop without growing, or grow without developing or do both at the same time. It is argued that that there can be development without growth or prosperity without growth, examples being gain in knowledge without economic growth. , or what is called sustainable development without growth. (H Daly, 1999, Daly & Farley, 2004). *This Thesis has considered development process as a function of economic processes, being open cyclic systems, which, in turn, are functions of elementary processes which are physical, chemical and biological in nature, each having its own energy matter input, production of goods and services and generation of waste and waste heat*. These are governed by the Thermodynamic laws. The topic of growth, development and sustainable development is dealt with in more details in Chapter 4, where the framework developed at the end of this Chapter has been carried forward.

2.7.2 Laws of Thermodynamics

The First Law of Thermodynamics is given below:

$$\Delta E = Q + W \qquad (2.6)$$

where ΔE is the change in internal energy[33], Q is amount of heat exchanged with surroundings and W is the amount of work done. Internal energy of an isolated system is constant. (Atkins & Paula, 2010, Cengel & Boles, 2011).

33 Internal Energy: In thermodynamics, the total energy of a system is called its internal energy. It is the total kinetic and potential energy of the molecules in the system. The total energy of a system is a state function (Atkins & Paula, 2010). In general internal energy consists of sensible, latent, chemical and nuclear energies (Cengel & Boles, 2011). Point particles and rigid bodies, fictitious model systems of Classical mechanics that do not exist in nature, are not thermodynamic systems. A point particle can neither rotate nor vibrate and, thus, cannot store energy within it; and hence cannot have internal energy (Leff, 2012).

The Second Law is about entropy[34,35] of the system and surroundings change when heat is exchanged between the two. If Q is the amount of heat exchanged at temperature T (by the system, say), then change in entropy can be stated as:

$$\Delta S = \frac{Q}{T} \tag{2.7}$$

This implies that

$$Q = T\Delta S \tag{2.8}$$

$$T = \left(\frac{Q}{\Delta S}\right)_V \tag{2.9}$$

The Eq 2.8 and 2.9 also define heat and temperature. Temperature can be seen as a measure of tendency to give up energy spontaneously to the surroundings (Chou, 2008).

Substituting the value of Q in Eq 2.6, we get:

$$\Delta E = T\Delta S + W \tag{2.10}$$

The above equation is valid as long as the temperature of the system is constant, which is true if the heat capacity of the system is large (as for a reservoir), so that the heat flow Q causes a

---

34 Entropy: There exists a function of the thermodynamic coordinates of a system whose value at the final state minus its value at the initial state equals the integral $\int_i^f \frac{dQ}{T}$ and is called Entropy as named by Rudolf Julius Emmanuel Clausius (1822-1888) in 1865 -In his own words "I propose to call the magnitude S the entropy of the body, from the Greek word (τρωπη) transformation. I have intentionally formed the word entropy so as to be as similar as possible to the word energy" (Zemansky & Dittman, 2011, Howard, 2001, Clausius, 1875). The entropy is an index of the tendency of a system to undergo spontaneous change; it is a measure of the state of differentiation or distribution of the energy of the system (Haynie, 2008). However, the 2nd Law does not imply any particular time scale for an event to occur even if its spontaneous. These are guided by energy barriers and kinetics of the system. (Glucina, Mayumi, 2010). Entropy bears significance only for systems that store internal energy, but not for point particle or a rigid body, the two mainstays of classical mechanics that do not stores internal energy, and their entropy values are zero and unchanging (Leff, 2012). Entropy is the measure or the index of energy dispersal at a temperature T (Lambert, 2002)

35 Several types of entropy are found in literature: Classical thermodynamic (Clausius Entropy), Statistical Entropy (Boltzmann), Shanon's Entropy of Information, Configurational Entropy, Gibb's Entropy, von Newmann Entropy, Negentropy (Schrodinger), Conformational Entropy and Renyi Entropy to mention a few. This Thesis uses the classical thermodynamic entropy only.

negligible small change in temperature of the system. The equation only gives a change in the entropy and not the initial or final values. Every irreversible process increases the total entropy of the universe. **A process that would decrease the total entropy of the universe is impossible**. A reversible process causes no change in the total entropy of the universe. It is possible to decrease the entropy of a system, but only at the expense of increasing the entropy of the surroundings by at least as much (usually more) (Giambattista, 2008).

2.7.3 Entropy Change of a System and Surrounding

To determine entropy change of a system and its surrounding, it is firstly important to put the First Law of Thermodynamics into action by carrying out energy and mass balance as below:

$$E_{input} = E_{output} + \Delta E \qquad (2.11)$$

$$M_{input} = M_{output} + \Delta M \qquad (2.12)$$

where E_{input} = Energy input to the system

E_{output} = Useful Energy or Work output from the system

ΔE = Unavailable energy, waste heat

M_{input} = Matter input to the system

M_{output} = Useful Matter or energy output from the system

ΔM = Waste matter in gaseous or liquid or solid state

In case of multiple streams of energy and matter input-output, the eq. 2.11 and 2.12 can be rewritten as:

$$\Sigma E_{input} = \Sigma E_{output} + \Sigma \Delta E \qquad (2.13)$$

$$\Sigma M_{input} = \Sigma M_{output} + \Sigma \Delta M \qquad (2.14)$$

One could also define efficiencies of energy and matter use as given below:

$$\eta_E = \frac{\Sigma E_{output}}{\Sigma E_{input}} \tag{2.15}$$

$$\eta_M = \frac{\Sigma M_{output}}{\Sigma M_{input}} \tag{2.16}$$

There are three ways entropy could be generated or transferred: heat transfer, mass transfer and entropy generation due to irreversibilities. When Q amount of heat (or ΔE waste heat) is transferred from system to surrounding or vice versa at the boundary at absolute temperature T, the associated entropy change is given by:

$$\Delta S = \frac{Q}{T} = \frac{\Delta E}{T} \tag{2.17}$$

If this heat was not rejected by the system, the system could get heated up instead which may not be safe for the system. The excess heat must be removed even by applying special cooling systems. (Cengel & Boles, 2011). Based on the above analysis, let us now construct an economic system (or a subsystem as a part of the larger earth system).

2.7.4 Interactions of the Economic Sub System as part of the Whole Earth system

The economic subsystem is a part of the larger earth system both of which are governed by the laws of thermodynamics as can be seen from the discussions from the preceding sections. Here it would be pertinent to mention, that the present Thesis is limited in scope to examine application of thermodynamics, especially the Entropy Law, to the development process in as much as that development process is a function of a set of economic processes which in turn are functions of, what NGR calls elementary processes, physical, chemical and biological in nature and have their own energy matter interactions. The application of thermodynamics in relation to production of “low entropy” resource i.e. energy and matter (and their relations with low entropy energy received from the sun and further interactions), the manner of interactions of “high entropy” waste in the biosphere (through complex cycles of material circulation such as hydrological or carbon cycles or atmospheric processes etc.) are beyond the scope of the Thesis as the same entails empirical large scale calculations of energy use and entropy in the various feedback loops of several subsystems that are operating continuously in nature and the economic process. The Thesis assumes that on the source side there exist “low entropy” matter and energy that are getting transformed at rates much faster than the rates of their rejuvenation, and that “high entropy” waste accumulate in the biosphere on the sink side at rates faster than they can be assimilated by the various natural cycles. However, these arguments shall be used in the subsequent chapters to understand sustainability and its relationship with entropy law.

Therefore, within the limited scope of this study, it can be concluded from the arguments put forth in this Chapter that the economic processes, which are comprised of production and consumption processes, are part of a larger earth system which is closed system in the larger sun-earth-space universe (receiving only solar energy from the sun, and releasing equivalent amount of entropy back into space, lest the system gets heated or cooled); and the economic production and consumption systems are open systems exchanging energy and matter from the larger earth system. This is depicted in Fig. No. 2.2 by revisiting the Fig No. 2.1. It shows that the earth system[36], being a closed system, receives solar energy (E) from the sun at 5760 K temperature, and sends back energy to the space at 273 K. The earth system is shown at temperature 298 K[37].

36 Earth received short wavelength solar energy from the sun (at a rate of ~238 WM^{-2} , and emits the same amount back to the space (Kleidon & Lorenz, 2004). This is an ideal situation. However, the NASA (2014, 2016) indicate that the earth system receives at the top of the atmosphere an insolation of 340.4 Wm^{-2}, and is able to send back only 339.8 Wm^{-2}, thus, retaining 0.6 Wm^{-2} flux into the earth system which would be causing warming of the system. Another study indicated net retention by the earth system to be 0.9 WM^{-2} (Trenberth, Fasullo, and Kiehl, 2008)

37 The mean surface temperature is taken to be 15^0C, which is 288 K. Research showed that the global mean temperature is 287 K (Trenberth, Fasullo, and Kiehl, 2008). However, in this study, temperature of the surrounding has been taken to be 298K (which is normally considered room temperature)

Since earth is a closed system and has its own internal energy, it must send back to space all energy that it receives from the sun constantly. If it sends back more energy than it receives, the system would start getting cooler, while if it sends back less energy, the system would start getting warmer. Since it would be nigh impossible to calculate the internal energy of the earth system, one needs to look at energy balance to see if there is any excess energy getting retained by the system or any excess of energy emitted into space. The earth system is complex, as one needs to consider energy at the top of the atmosphere, in the atmosphere and at the earth's surface (NASA, 2014). The earth system's energy balance, in absence of any living organisms would continue unperturbed till the solar energy lasts. However, if living organisms (including humans in pre-industrial age) are introduced in the earth system, and they live off the primary production alone (barring the waste emissions that might change the atmospheric conditions[38,39]), there might be negligible perturbations in the energy balance at various levels in the earth system. Now if post industrial revolution modern man (Homo economicus) are introduced into the earth system, the huge mass of locked energy in form of fossil fuels would get unlocked and produce significant perturbations in the energy balance.

38 Refer to Wilkinson, Nisbet, and Ruxton (2012) for an alternate theory for extinction of dinosaurs, and Mojzsis (2001) and Yamaguchi (2003) to see how early earth atmosphere evolved from anaerobic to aerobic.

39 Perturbations can also be brought about by mass extinction and loss of biodiversity. Refer Ceballos, Ehrlich & Dirzo (2016) who argue that "beyond global species extinctions Earth is experiencing a huge episode of population declines and extirpations, which will have negative cascading consequences on ecosystem functioning and services vital to sustaining civilization", and the authors term it as "biological annihilation".

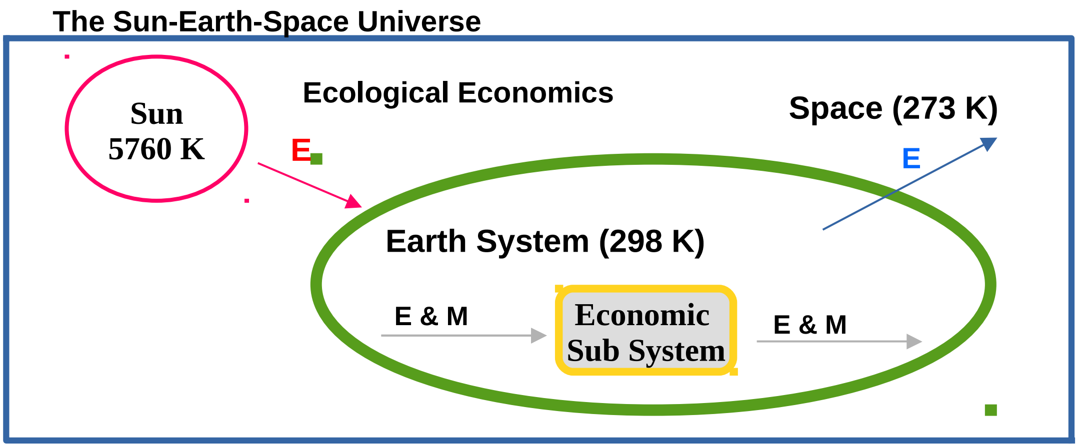

Fig. No. 2.2: The Economic Sub System

Though there are claims in literature that entropy generated through anthropogenic sources are only a negligible fraction of the entropy generated from the sun (Weiss, 1996), such studies do not seem to explain the evolution of the earth's atmosphere, or a possibility of species extinction due to waste emission. Since the earth's atmosphere (surrounding for the economic sub system) has its own internal energy, being the sum of translational, rotational, vibrational and potential energies of all the molecules held by it, any release of additional matter and energy into the atmospheric system is likely to cause perturbations in the atmospheric system, the rule of energy balance applies there. The pumping of additional waste material from the economic sub system is likely to upset the energy balance of the atmosphere causing it to either to get cooled or warmed. Studies indicate the earth system is retaining part of the incoming solar energy, transmitting about 0.6 to 0.9 Wm^{-2} less than what it receives from the sun. (NASA, 2014, 2016, Trenberth, Fasullo, and Kiehl, 2008).

The economic production and consumption processes[40] generate high entropy in the surroundings (by virtue of energy matter interactions). Though the source of energy might have originated from solar energy million years ago, it is matter nevertheless, and “matter matters too”

40 According to Baumgartner (2002) economic process consists of production, consumption and reduction – reduction meaning recycling of waste; and if we add distribution to it, the system may be called production, distribution, consumption and reduction, PDCR, as a complete description of the economic process

(NGR, 1979), and its exploitation adds additional flux to the energy balance of the earth system. Since the earth is a closed system, the high entropy generated through rapid anthropogenic transformations, in form of waste heat and CO_2 emissions would add to the normal budget of the earth system's energy and entropy, resulting in inefficient transfer of energy/entropy back to space. NASA (2014) and other studies (Trenberth, Fasullo, and Kiehl, 2008), in conclusion, can be used to vet this approach proposed here. The attempt here is to bring the economic subsystem directly within the fold of the earth system through the interplay of the metabolic processes in nature and the economy and the resultant entropy generation and waste heat accumulation that could lead to rise in ambient temperature and climate change.

2.8 Conclusion

The economic sub system framework proposed above is a thermodynamic system, and predicts heating and cooling of the earth system, which is a closed system, by perturbations from within the earth system caused by the economic sub system. The theoretical framework of the Thesis, thus, vindicates the theory of NGR proposed in 1971 in his magnum opus The Entropy and the Economic Process. As literature review suggests, NGR's theory of 1971 was prophetic but least understood by getting mired into the dogmas of metaphor and analogue. Global warming and threat of climate change have once again brought NGR to centre stage and his relevance is like never before. The reemergence of NRG's theories in wake of several economic meltdowns[41] and climate induces catastrophe in the recent past and the impending global warming is inevitable. There are very few real world studies (Lozada, 1999, Ruth 1995, Krysiak & Krysiak 1986, Ayres et al 2004, 2006, Alverado 1999) on the entropy law and economic process and its impact on the earth system. The biggest challenge is how to make the economic processes less entropic, and how to bring to minimum the consumption of mass and energy in the economic sub system that

41 Recent economic meltdowns- UK (2007-09), US (2007-09, 2001) Russia (2014-15) to mention a few.

cause maximum perturbations in the energy/ entropy balance of the earth system. Providing a solution to this challenge is beyond the scope of the Thesis, yet it brings to fore the larger issues of economic growth, development and sustainability from the entropic perspective. These topics have been examined in more detail in Chapter 4.

CHAPTER 3

3 Research Methodology

Our most urgent task is to convince the public that the consumption of energy and matter must be drastically curtailed in the developed countries, while greater amounts must be devoted to saving from hunger and squalor the large masses of the underdeveloped countries. (NGR, 1979, p21)

3.1 Introduction

This Chapter deals with research methodology. Two approaches have been adopted while conducting the study. An extensive literature review on the topic, which is a transdiciplinary subject, was conducted and case study methodology was adopted in order to answer the Research Questions. As can be seen from the Chapter 1 which set the research context, as well as Chapter 2, we are at a critical juncture of our long million year old journey where never before such high CO_2 levels were observed in the atmosphere due to anthropogenic causes, and on the other hand a growing population of more than 7.4 billion people demanding for resources and growth. The relevance of NGR and his theories was never more relevant and so very apparent. While deciding upon the research methodology, realizing its vast domain and varied scope, it was important to go through more than 45 years of research carried out since the days of NGR when he first published his magnum opus "*The Entropy Law and the Economic Process*" in the year 1971, and more than two centuries behind to 1850 to look at the origins of the Laws of Thermodynamics. Therefore, the literature review centered around developments leading to emergence of Ecological economics and bioeconomics of NGR, differences with NCE, entropy law and economic process and criticism thereof, thermodynamic systems and laws of thermodynamics, ecology and ecosystems, theories of economic growth, development and sustainable development, steady state economics, degrowth, circular economy, global warming and climate change. The topics covered also included energy, efficiency, exergy, emergy, embodied energy, fund flow and stock flow, ecosystem services and carbon footprint. The figures below graphically depict the fields of study and broad range of topics covered and their inter-relationships.

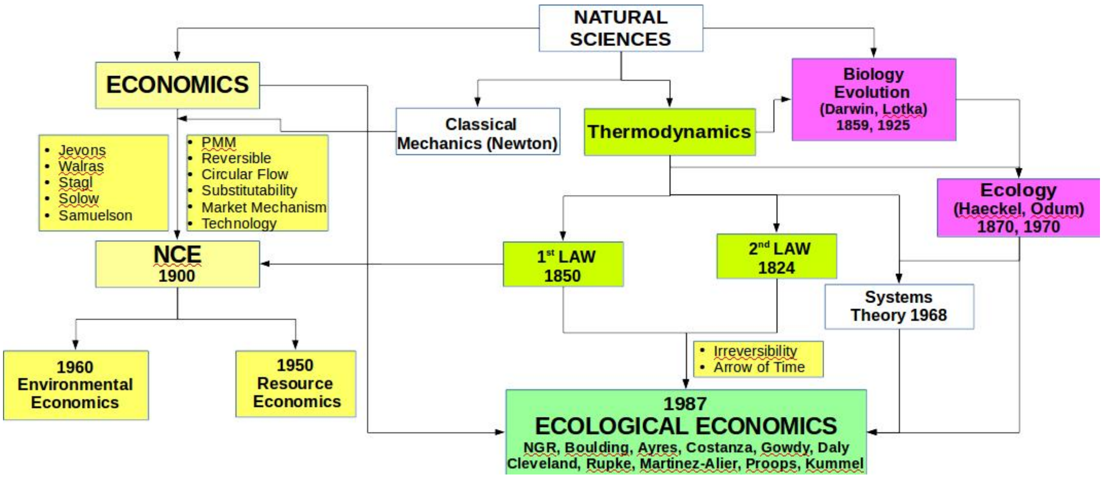

Fig. No. 3.1: Transdisciplinary Approach: Science and Economics

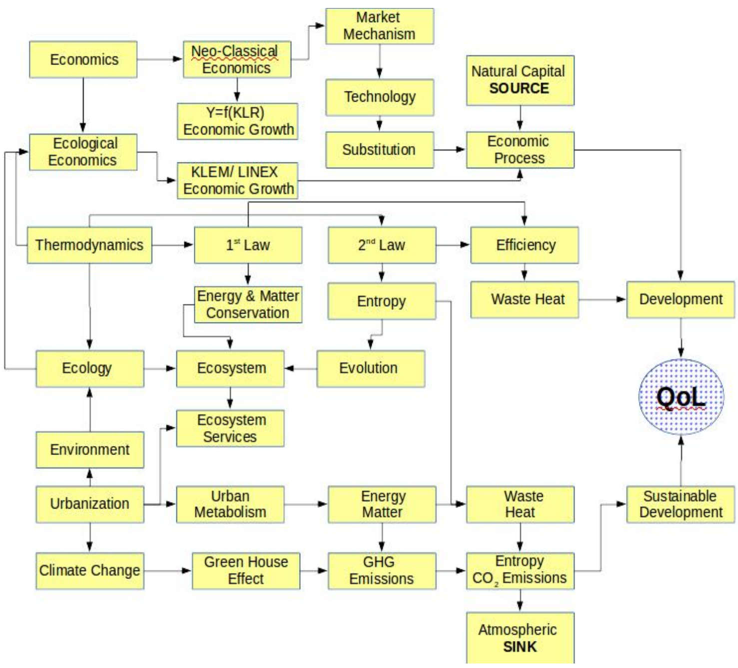

Fig. No. 3.2: Conceptual Framework of Study

Ecological economics is a post normal inter disciplinary emerging science quarter of a century old drawing very heavily from economics, thermodynamics, ecology, evolution, systems theory, and information theory (see Fig. No. 3.1), as a result of which researchers belonging to different fields bring their strengths through their well established methods and analytical tools but leave general readers and novices in a quandary. The present study would touch upon topics such as laws of thermodynamics, entropy, efficiency, waste heat, ecosystem, ecology, environment, urbanization, energy matter interactions, green house gas emissions and climate change, source and sinks, as well as frontiers of the NCE such as production function and substitutability. The conceptual framework of the study, as to how it organizes and links various themes and topics is depicted in Fig No. 3.2. Moreover, entropy being the central theme of the present research study, it was found that in a heap of more than 550 research publications that reviewed, only 20 odd papers dwelt on entropy calculations in real world economics processes, while the rest dealt with Shanon's Entropy, input-output analysis, exergy analysis, emergy analysis, embodied energy analysis, material flow analysis, maximum entropy production, multi criteria decision making, energy and mass balance calculations, Life Cycle Assessments (which are essentially mass and energy balance calculations) – Cradle to Grave, Cradle to Cradle, Cradle to Gate, ecosystem service valuations, ecological footprints and carbon emission calculations. On entropy topic, maximum papers were encountered on GIS and Shanon's entropy application relating to urban sprawl, forest cover loss etc.

Thus, this research study is unique in proposing a real world development process case study, taking urbanization as a development process, and working out the thermodynamic entropy (as opposed to information entropy) in a number of economic processes.

3.2 Brief Discussion of methodologies used in 45 Years of Research on NGR

Glucina and Mayumi (2010) have summed up the various methodologies used in studies of thermodynamic constraints on economics focusing on the past 40 years of research on NGR in their monumental study entitled “Connecting thermodynamics and economics- Well-lit roads and burnt bridges”. Two different models have been used by various researchers namely

1. **Descriptive model**: This “relies on words and diagrams to convey simplified version of reality that is a precursor of investigation. This type of model is necessarily qualitative and may also be thought of as the pre-analytic vision”.
2. **Mathematical model**: This model “transfers the concepts from the descriptive model into mathematical language, which ideally can be used to solve problems quantitatively.

The energy's contribution to the economy still remains to be resolved. For ecological economists, energy is a fundamental factor enabling economic production, and the economic growth and energy use are difficult to decouple solely by developing and deploying energy efficient technologies. The focus needs to be on decarbonizing energy supplies (Ockwell, 2008).

The mathematical model attempts to quantify thermodynamic limits to generate desired output from economic processes and these have been investigated at the level of individual processes. Application of thermodynamics to systems are system specific and depend upon the actual variables such as temperature, pressure, nature and constitution of the chemical species present in the system, as well as the quantities of heat and work exchanged at the system boundary (Glucina and Mayumi, 2010). Thus, it is difficult to arrive from industry specific analysis to aggregated economy-wide quantification. Very few such studies are available such as by Ruth (1995, 1995a, 1995b), Lozada (1999), Kummel (1989), Kummel & Schussler (1991), Faber, Niemes & Stephan (1995), Rechberger and Gradel (2002), Ayres et al (2004, 2006), Gößling-Reisemann (2001, 2006) , Alvarado (1999).

Econophysics/ Physical Economics Analogies: Applying physical laws to economics has been there for long. This thesis is based on the NGR's criticism of NCE for employing Classical mechanics models (meant for rigid bodies and point objects) to real world economic processes which are thermodynamic in nature. Application of the laws of thermodynamics is yet another example, but can be excused as the two Laws of Thermodynamics are universal laws and apply on all sciences and streams of knowledge that deal with energy and mass interactions and transformations. Besides the application of the two thermodynamic laws, one can find other examples, most famous of which is application of PV=nRT to economics. The most recent and most novel is a complete set of analogous state variables (extensive and intensive) along with the 1st and 2nd laws of Physical Economics[42]. See the Table below. (Richmond, Mimkes, Hutzler, 2013).

Economics			**Physics**		
	Name of Variable	**Unit**		**Name of Variable**	**Unit**
M	Money	Currency	Q	Heat	Joules
K	Capital	Currency	E	Energy	Joules
P	Production	Currency	W	Work	Joules
λ	Dither	Currency	T	Temperature	Kelvin
Se	Economic Entropy	*Dimensionless*	S	Entropy	Joules K^{-1}
Π	Economic pressure	Currency	P	Pressure	Nm^{-2}
A	Freedom for action	*Dimensionless*	V	Volume	m^3

However, thermodynamic formalism may be of little use in economics. It is also not clear what system specific mathematics are relevant to economics (Glucina & Mayumi, 2010). Given the complexity of the entropy law and its application to economics, no such arithmomorphic approach has been adopted in this study.

42 1st Law of Economics: Equivalence of Monetary (M) and Productive (P) circuits expressed by

$$\delta M = dK - \delta P$$

2nd Law of Economics: $\delta M = \lambda dSe$

Entropy Studies by Gabriel Lozada: Lozada completely dismisses the information theory entropy methodology in the context of entropy in which temperature is absent. His studies are based on real world economic processes applied in the extractive metallurgy industry. He asserts that the idea of thermal entropy is related to heat flow. Lozada has also taken into account the configurational entropy which arises due to mixing of matter and changes in concentration of materials (as these also change the chemical potential values of the material in question) specially the Stage I processes in metallurgy that deal with crushing and grinding of ore and its concentration enhancement before proceeding to the next stage of metal separation, and the final stage of high level purification (Lozada, 1999). The total entropy change, thus, is represented as:

$$\Delta S = \Delta S_{configurational} + \Delta S_{therma.system} + \Delta S_{therma.surrounding} \quad (3.1)$$

for a chemical process of extraction involving a generic equation of two reactants (A & B) and resultant product C:

$$A+B=2C \quad (3.2)$$

Using actual values for the reactants and products, Lozada (1999) arrived at the minimum entropy change requirement for copper ore processing at 0.41 MJ K^{-1} $(1000\ Kg)^{-1}$ of copper. This entropy change in the system-surrounding universe is under very ideal conditions, and is likely to be many times more for poorer ores. The closer the actual entropy would get to this value of 0.41 MJ K^{-1} $(1000\ Kg)^{-1}$, the harder it would be to reduce entropy increase as one must approach ever closer to the ideal conditions of zero friction, resistance etc. According to Lozada (1999), this has direct economic significance in the sense that the minimum energy required for the process would be not less than 123 MJ $(1000\ Kg)^{-1}$ of copper. When multiplied by the cost of energy, it would give the direct minimum cost of production in terms of entropy requirements itself. Lozada (1999) further asserts that as richer ores would get processed, we would be left with poorer ores that would generate many times more entropy. This is a clear indication of degeneration of natural resources. According to Lozada (1999), “The prosperity of future generations depends partially upon the endowment of rich natural resources they inherit”.

3.3 Sollner/ Baumgartner Classification System

Sollner (1997) and Baumgartner et al (2004) devised a classification system for categorizing research using thermodynamics into economics. There are four classes. The class 4 has 5 sub classes. The classification is given below:

1. Isomorphism of formal structure between thermodynamics and economics
2. Analogies and metaphors between thermodynamics and economics
3. Energy, entropy and exergy theories of value
4. Thermodynamic constraints on economic action
    (a) Models incorporating mass and conservation of mass
    (b) Models incorporating energy and conservation of energy including embodied energy
    (c) Models incorporating entropy and entropy generation
    (d) Models incorporating energy and entropy (and also exergy)
    (e) Models incorporating mass, energy and entropy

As per the above classification, this study falls in Class 4e: “**Thermodynamic constraints on economic action: Models incorporating mass, energy and entropy** ”

3.4 Objective of the Study

The research was conducted with two objectives in mind:

1. To understand the relationship between entropy and the development process and link it to sustainable development.
2. To conduct a case study to verify the above relationship.

3.5 Literature Review:

Literature on the Entropy and Economics Relationship: An initial review of literature revealed that it was NGR's work that strongly for the first time focused in depth on thermodynamics and economics relationship, both the first and second laws were considered important. Two schools of thought emerged- one in support of NGR and the other that dismissed his approach.

The main literature pertains directly to works of NGR and school of thought that supported his views including works of his students, Herman Daly, John Gowdy, Kozo Mayumi and works of Ecological economists (NGR being one of the pillars of Ecological Economics) namely Robert Costanza, Robert Ayers, Mauro Bonaiuti, R. Kummel, Joshua Farley, Sigrid Stagl, Sergio Ulgiati, Joan Martinez- Alier, Cutler J. Cleveland, Stefano Zamagni, M. Giampietro, Peter A Victor. A limited literature pertains to the works of critiques of NGR like T. Young and Khalil. Considerable Literature where Entropy law and NGRs theory was considered as foundational in understanding the Biophysical limits to Economic Growth and environmental instability due to rapid development of nations through intensive energy and resource use. This includes literature on planetary boundaries and warnings of overshoot. The key authors are Rifkin, Rees, Wakernagel, Kummel, Martinez-Alier, J Farley, Rockstrom, Lovelock, Henrick Robert and Gunter Pauli.

Direct Interview & Communication Methodology: Direct email communication was established between some of the students of NGR and other researchers to understand the correct perspective of NGR and the counter arguments against his theories. They have shared their research papers and working papers which enriched my understanding on the subject, notable among them being John M. Gowdy, Kozo Mayumi, Jurgon Bennewitz, Reiner Kummel and Elias L Khalil. The author got an opportunity to meet some of the leading ecological economists namely John M Gowdy, Joan Marinez-Alier, Robert Costanza, Anthony Friend, William Rees, Mathis Wackaernagel, Joshua Farley, Bina Agrawal at the ISEE Rio+20 XII Biennial Conference from June 20-22, 2012 at Rio De Janiro, and also presented a conference paper entitled "A Study On (Un)Sustainable City From Entropy Perspective". At the conference, only two papers were presented on entropy, about which a serious discussion took place as to why only two entropy related research papers[43] were presented.

Ecological Economics Winter Course at Oxford: In December, 2012 a 5 day Oxford Winter Course in Ecological Economics at St. Hugh's College, Oxford from 17th to 21st December was attended by the author, organized by Dr Stanislav Shmelev, Senior Visiting Research Associate, School of Geography and the Environment, University of Oxford and Associate, Cambridge Centre for Climate Change Mitigation Research, University of Cambridge. Ecological economics research scholars from various countries participated. It was a good participatory peer group learning through discussions.

Going to Basics: Moving beyond economic process to development process and looking at the entropy-development relationship – is the key theme of this study. Standard Thermodynamics text books by PW Atkins, Cengel & Boles, Zamansky & Dittman, D.T. Haynie (Biological Thermodynamics), Glasstone (Physical Chemistry) were referred that helped in analyzing the

43 The other presenter being – Anthony Marcus Friend, Institute of Environment, University of Ottawa

thermodynamics economic process relationship and selecting relevant definitions and formula in further building a stronger analytical framework for the study. Another dimension of the study was understanding global warming, climate change and the earth system, so that appropriate relationships could be construed between the economic processes/ development processes and the biospheric and atmospheric constraints, especially the GHG emissions due to anthropogenic causes.

Journals Referred: The key journals referred were: Ecological Economics, Energy, Energy Policy, Entropy, Sustainability, Journal of Industrial Ecology, Ecological Modeling, Open Journal of Applied Sciences, Journal of Environmental Management, Entropy, Nature, Scientific American, American Journal of Economics & Sociology, International Journal of Bioeconomics, Journal of Chemical Education, Science & Society, Thermodynamics to mention a few.

Published Reports: Several reports of various national and international organizations were referred to. Energy reports of IEA, GEA, BP, reports of WRI, IPCC, World Bank, United Nations, Human Development Reports, IIASA publications, are the key reports referred to in the study.

Websites and Portals: Reference was gathered from several websites of repute such as Mauna Loa Observatory, NOAAA, IPCC, Carbon Dioxide Information Analysis Center (CDIAC), IEA, NASA etc.

3.6 Case Study Methodology

A case study as a research method looks at the setting as a whole, describing the context, the actors involved and the processes as well (Gagnon, 2010). A case study can have several purposes – provide description, test a theory or generate a theory (Eisenhardt, 1989). A case study may have a singular or multiple cases and can be descriptive, comparative or analytic

(Gagnon, 2010, Gillham, 2008). Yin (2009) has identified some specific types of case studies: Exploratory, Explanatory, and Descriptive. Stake (1995) included three others: Intrinsic - when the researcher has an interest in the case; Instrumental - when the case is used to understand more than what is obvious to the observer; Collective - when a group of cases is studied. The unit of analysis is a critical factor in the case study. It is typically a system of action rather than an individual or group of individuals (Gagnon, 2010, Yin, 2009). The case study research method employed here is an instrumental and collective case study. While the relationship between entropy, economic and development process has been explored at length in Chapter 2 and 4 using literature review and content analysis methodology, an attempt at understanding the same in quantitative terms has been made through the case study methodology, taking the case of Guwahati city. Thus, the case study enables to answer the research question "Can the relationship between entropy and development process be understood from the sustainable development perspective?"

3.6.1 Why City Case Study?

J Martinez-Alier and F Demaria (2016) speak of how to make cities "less unsustainable" and acknowledge that "Urban areas are becoming the main habitat for majority of the global populations". Cities are considered as open systems which depend on their surroundings for the provision of natural resources that are indispensable for development of urban centers. Studies reveal that cities have a parasitic character shown by the fact that though they cover 2% of the earth's surface, they consume 75% of the natural resources. The urbanization process draws resources from the source (land and water resources) and the wastes are dumped into the natural sinks. The second law of thermodynamics, the entropy law, binds the capacities on the source and the sink. The rapid production and consumption processes that take place as development progresses, lead to the transformation of low entropy, matter (natural capital) and energy to high entropy wastes and useful output in the form of improved infrastructure and other man made capital. Therefore, city presents a most comprehensive and all encompassing view of development as we understand. Per capita energy consumption in cities is high due to the high standards of living and improved quality of life. The urban metabolism, thus, is an interesting case in trying to understand the energy and matter transformation due to improved life styles and high consumption leading to increased emissions.

3.6.2 The City Case Study Methodology

In order to study urbanization from an entropic perspective, four sectors[44] were identified. A detailed methodology has been worked out to achieve the objectives of the case study based on literature review especially focusing on key aspects of urban metabolism, energy use, urban growth, city carbon footprints, deforestation, AFOLU from urban perspective to mention a few. The various methodologies of CO_2 emission estimation, waste heat estimation were also searched through in available literature. The detailed sector methodology followed in carrying out the city case study is outlined in Chapter 5 along with a brief discussion of results and analysis. This is mainly because each economic process and its constituent physical and chemical need to be looked at individually to understand entropy generation, as there cannot be any uniform treatment to this. In the paragraphs that follow, a brief overview of the case study methods has been given.

3.6.2.1 Objective of the Case Study

Development and emissions are intrinsically linked to each other, which is true in the urbanization scenario. Urban emissions are a function of mobility, shelter and life styles. Though notionally established through global and national level data and statistics, and the local level

44 The sectors are 1. Electricity Consumption of the city, 2. Fossil fuel consumption (Petrol, diesel, LPG and Kerosene), 3. Building, 4. AFOLU (Agriculture Forestry and Other land Use). The sector details along with detailed sector methodology has been presented in Chapter 5.

nuances have mostly not been explored. The relationship needs a validation through quantification in terms of emission on one hand and development and life style parameters on the other. The broad economic processes also need to be broken down into locally measurable quantities. To validate the findings from the literature review, the case study of Guwahati city has been taken up following objectives:-

1. Establish development and entropy linkage (Is there a correlation between the two?)
2. Establish the nature of the linkage (Directly proportional or inversely proportional?)

3.6.2.2 How is Development Measured in the Case Study?

City has been seen as an organized entity that intakes energy and matter and grows and in the process emits waste and waste heat. The following measures of growth have been taken into consideration:

Growth in Population: Population is a good measure of societal metabolism, and hence also of city metabolism. Growth in population of the city as a time series has been taken as one of the independent parameters in the study. Available census data is the best independent source of population. In the instant case study, population data was collected for the city of Guwahati from 1911 to 2011.

Growth in City Built Up: The city growth is visible in terms of increase in geographical extent of the city which is measured in units of, say sq km or hectares. As the city grows, more and more land area would be covered under roads, residential housing, commercial complexes and support services. This growth can very easily be identified using satellite imagery. In the instant case study, satellite data was used to get growth pattern from 2003 to 2015. However, published topographic survey maps were used to assess the growth in the period from 1911 to 1986.

Growth in Construction Activity: Construction per se is one of the most visible types of growth in a city where smaller buildings give rise to bigger buildings (without much impacting the built up area), and new areas are also colonised which leads to increase in built up area of the city. In the instant case study, the building constructions activity was indirectly inferred from the floor area (say in sq m) that was allowed by the urban local body/ development authority for construction, what is called grant of building permission. While the city built up data is gathered/ inferred from mapsets and satellite images and measured in sq km, the building construction activity was measured in sq m of floors supposed to have been added annually.

Growth in Number of Vehicles: Another growth parameter taken for the case study was the number of vehicles in the city. It was directly inferred from the annual registration of vehicles data available with the Transport authorities.

Growth in Electricity Consumption: Electricity is the high quality energy, consumption of which is hallmark of any developed urban entity. Electricity availability can be also termed as the primary requisite for urban growth. All the complex development and economic activities such as education, health, service delivery, industrial production would be difficult in absence of electricity.

3.6.2.3 Interconnects of the Growth Parameters

Of the five parameters suggested above, there are several interconnects and linkages between them. Some of these are discussed below:

Population: Population is the most independent parameter, and directly impacts all other parameters. Therefore, it may be taken as a fundamental measure of societal metabolism, especially in an urban context.

Built Up Area: Built up area is linked up with population rise, as more people join the city, the city limits are bound to grow. However, the question is not that population is increasing, and thus, built up is increasing. The primary question is why people are moving to a particular city? The city must be offering (or continue to offer over a longer periods of time) opportunities for better health care, better education, better living condition, and above all better job livelihood and growth opportunities. Therefore, while built up may correlate very well with population (more people more space required and hence higher built up), it is taken as an indicator of growth of the economic activities (more schools, hospitals, offices, service centres, processing centres so on and so forth). Therefore, in the instant study, built up has been taken as an indicator of economic growth.

Vehicle Growth: Growth in vehicular numbers is also directly related with population, but on a second glance, it would turn up that its a reflection of rise in purchasing power. Therefore, it is indicative of the rise in income.

Growth in Electricity Consumption: growth in electricity consumption can be positively attributed to population (more population, more power), and it can also be attributed to built up (more buildings or streets, more power). Built up, in turn, as already discussed, is attributed to higher population but more to growth of economic activities. However, as would be seen later in Chapter 5, growth in electricity consumption could also be attributed to “Life Style” (and also to rise in income). However, as electricity is primarily needed to power appliances (comfort cooling, heating, lighting, electronic gadgets, kitchen appliances, computers and information technology systems etc.), it can be said that electricity is a good candidate as “Life Style” and “Quality of Life” indicator.

Life Style Indicators: Based on the above discussion, it is apparent that while built up of city can be a good measure of economic growth of the city, life style can be inferred from higher energy/electricity use and no. of vehicles. According to Diamond (2003), as people move to higher strata in the society, as their socio-economic status improves, their energy requirements go up. Therefore, electricity consumption and vehicle are good candidates for life style indicators. Hence, it is proposed to take the following as life style indicators for this study: 1. Per Capita Power (W), 2. No. of vehicles Per 1000 Persons (V). In an urban scenario, adopting from Dhakal (2008), who has considered three sector namely energy, economic and social sectors for assessing carbon footprint of cities, one can arrive at a simpler function for urban emissions:

$$\text{Entropy} = f\,(\text{Population, Buildings, Transport, Life Style}) \quad (3.3)$$

3.6.2.4 What is Economic Activity and How Arrived at?

The basic approach of the thesis is to measure waste and waste heat generation in a series of economic processes or activities that could be considered as a part of urbanization as a development process. This challenge has been met by resorting to the International Standard Industrial Classification of All Economic Activities (ISIC) under the aegis of the United Nations (UN ISIC, 2008). The version 4 of this document lists 429 number of economically meaningful activities and groups them in 21 sections (A-U), 99 divisions and 240 classes. These activities, according to ISIC are " defined as the use of inputs (e.g. capital, labor, energy and materials) to produce outputs. The outputs that result from the undertaking activities can be transferred or sold to other units (in market or non-market transactions), placed in inventory or used by the producing units for own final use". The activities relevant to the instant case study were selected from among the listed in the Code. Details can be seen in Appendix 2.

3.6.2.5 Accounting for Energy and Matter

The instant case study considers energy (as manifest in matter as fossils fuels and fuelwood), as well as high quality energy such as electricity (which is indirectly derived from matter such as coal- in case the power consumed comes from thermal sources) finally in Tera Joules (TJ). However, the data collection is in mass terms (metric tonnes and kilo litres) for all energy sources studied other than electricity. Conversion factors available in literature have been used to convert these energies from their mass units to energy units. Details have been given in the Chapter 5. All the quantities have been treated as annual input to the city system. In case of electricity, direct input has been taken in energy units (Million Units, where 1 Unit = 1 kWh), but the thermal component of it has been converted into quantity of coal used in the power plant to generate the requisite amount of power at the household level after accounting for all the losses from power plant to the delivery point at the doorstep of the consumer. The coal thus consumed is indirect mass (and energy footprint) of the electricity consumed in the city). In case of AFOLU sector, there are no direct mass or energy calculations carried out. Only the waste in form of CO_2 emission has been estimated.

In case of building study, mass of various construction material used such as cement, steel and brick has been estimated to arrive at the total energy consumed directly and indirectly as well as total entropy (direct and indirect) generated from the materials. Here, it must be brought to record that entropy generation from buildings have been worked out taking cradle to grave approach partially. This means that the building entropy shown annually also reflects the amount of entropy that the floor areas added annually would generate during their life time.

3.6.2.6 Accounting for Waste

The instant case study considers only two types of waste namely waste heat (which is thermodynamic and is heat loss by a physical or chemical processes), and CO_2 emission in each of the process studied. The instant study is unique in the sense that it combines the waste heat and CO_2 emission together into a single waste heat factor, and arrives at energy accounting for the city for 5 years in form of total (direct and indirect) energy use and waste heat generated. The study, thus, is able to come up with efficiency of energy use of the city system, which is the hall mark of the case study.

3.7 Research Methods

The task at hand for the research study included population projections, univariate and multivariate regression, correlation, scenario projections, calculation of efficiencies, CO_2 emissions and entropy calculations. While all standard statistical operations were performed using spreadsheet application, univariate and multivariate analysis were done using online free tools on the Internet (Xuru, 2016). Scenario projections were done using simple spreadsheet operations. The formulae used for population projection is given in Appendix-4. The methods used for efficiency, CO_2 emissions and entropy are briefly described in the sections that follow. However, since each of these require specific application of the formulae depending upon the process, details of methodology have been given in Chapter 5 separately in Section 5.5.8 to 5.5.11, as well as along with the sectoral case study at section 5.6.1.3 to 5.6.1.6, 5.6.3.2 to 5.6.3.3 and 5.6.4.4 to 5.6.4.5.

3.7.1 Efficiency

Efficiency of a process is given by:

$$\eta = \frac{E_{output}}{E_{input}} \tag{3.4}$$

where E_{input} is input energy and E_{output} is useful energy outputted by the conversion process.

If E_{waste} is known then,

$$\eta = \frac{E_{input} - E_{waste}}{E_{input}} \tag{3.5}$$

In case there are n number of processes involved in conversion of one form of energy into another, with each process having a conversion efficiency i, the overall efficiency of conversion is given by the formula:

$$\eta = \prod_{i}^{n} \eta_i \tag{3.6}$$

3.7.2 Methods for Estimation of CO_2 Emission

As per the IPCC (2006), there are three recommended methodologies for estimating CO_2 emissions namely Tier I, Tier II and Tier III. All the three methodologies have been used in the Case Study. The specific application of these as per the Case Study sector has been given in Chapter 5 section 5.5.9. The methods used in this study differ somewhat with methods deployed by some other authors. While Ramchandra et al (2015) studied emissions of Delhi, Kolkata, Hyderabad, Chennai, Greater Bengaluru, Greater Mumbai and Ahmedabad by considering CO_2 and non CO_2 emissions aggregated over several sectors, and for electricity consumption the authors deployed direct multiplication of emission factor with energy consumed, assuming 0.7 kg of coal was used in producing 1 Unit of electricity. They appropriately treated the source of energy for each city as regards the ratios of the mix of thermal and hydel. However, they do not account for losses in electricity transmission and distribution. On the contrary the present study takes 0.922 kg of coal per 1 U of energy consumed by accounting for the various losses. Kaneko et al (2003) studied carbon footprint of Asian mega cities by considering direct and indirect energy use in case of electricity. Sovacool & Brown (2010) studied carbon emission of 12 mega cities of the world including New Delhi. According to the authors the carbon footprint of Delhi per capita was 0.7 MtC. Butler et al (2008) studied 30 mega cities of the world including New Delhi. Sridhar (2010) reported CO_2 emission for cities of India arriving at 1.19 $MtCO_2$ per capita for metro cities on an average. However, the footprints are not comparable due to use of different methodologies in choosing sectors or different mix of GHGs. A major difference found was that none of the cities took into consideration CO_2 emission (indirect) from building construction activities arising out of cement usage, and electricity losses in transmission and distribution. Thus, this study is unique from other studies in this respect. As regards embodied energy of building materials and CO_2 footprint of building materials, it was found that Hammond & Jones (2008), Ramesh et al (2013) have reported embodied energy per m^2 varying from 5036 MJ to 5340 MJ, and 110 kgC. These figures are in close conformity with the values arrived at in the building case study (see Table No. 5.9 in Chapter 5). However, no entropy study for buildings was found in literature. This study is unique in this respect that it lays down detailed procedure for entropy calculation of buildings.

3.7.3 Methods for Estimation of Entropy generation

A system and surrounding are both components of the universe, which can be seen in this equation:

$$\Delta S_{total} = \Delta S_{univ} = \Delta S_{sys} + \Delta S_{surr} \geqslant 0 \qquad (3.7)$$

the system and surroundings collective represent the change in entropy. The entropy change of the surroundings is driven by heat flow and the heat flow determines the sign of ΔS_{surr} . Therefore, if we had an exothermic economic process at a constant temperature, the system would cause heat to flow into the surroundings, which causes ΔS_{surr} to become positive. If the amount of heat flow into the surrounding was ΔQ_{surr} , the entropy generation in the surroundings would be:

$$\Delta S_{surr} = \frac{\Delta Q_{surr}}{T_{surr}} \qquad (3.8)$$

However, due to Conservation of Energy theorem (the First law of Thermodynamics), we shall have:

$$\Delta Q_{surr} = -\Delta Q_{sys} \tag{3.9}$$

If the system is at T_{sys}, then the entropy change in the system would be given by:

$$\Delta S_{sys} = \frac{\Delta Q_{sys}}{T_{sys}} \tag{3.10}$$

As already stated, $\Delta S_{sys} + \Delta S_{surr} \geqslant 0$ relationship between the system and the surrounding would hold.

Within the city limits, entropy generation by various sub systems representing a process is worked out. Since each sub system contributes independently to the surrounding, summation would be used to arrive at a single entropy contribution from the city limits to the surroundings:

$$\Delta S_{City} = \sum_i \Delta S_i \tag{3.11}$$

where $\Delta S_{City} = \text{Entropy contribution of the City limits}$
$\Delta S_i = \text{Entropy contribution of } i \text{ th process}$

3.7.4 Entropic Indicators

Once the total city entropy ΔS_{City} is worked out, two indicators would be calculated for the city as given below:

1. Entropy Generation Per Capita (EGPC):

$$EGPC = \frac{\Delta S_{City}}{P_{City}} \quad \text{where } P_{City} \text{ is the Population of the city} \tag{3.12}$$

2. Efficiency of City System:

$$\eta_{CITY} = \frac{E_{INPUT} - E_{WASTE}}{E_{INPUT}} \tag{3.13}$$

where E_{INPUT} is the input energy and E_{WASTE} is the waste heat

3.8 The Case Study Process Flow

Each of the four sectoral case studies that comprise the Case Study of the Thesis, has its own data sources, time period for which data was available or could be collected, methods of data validation, methods of analysis for CO_2 emission and entropy generation. Each of these have been described in detail in Chapter 5. The broad Case Study methodology for each of the four sectors followed is depicted through a process flow diagram at Fig. No. 3.3 given below.

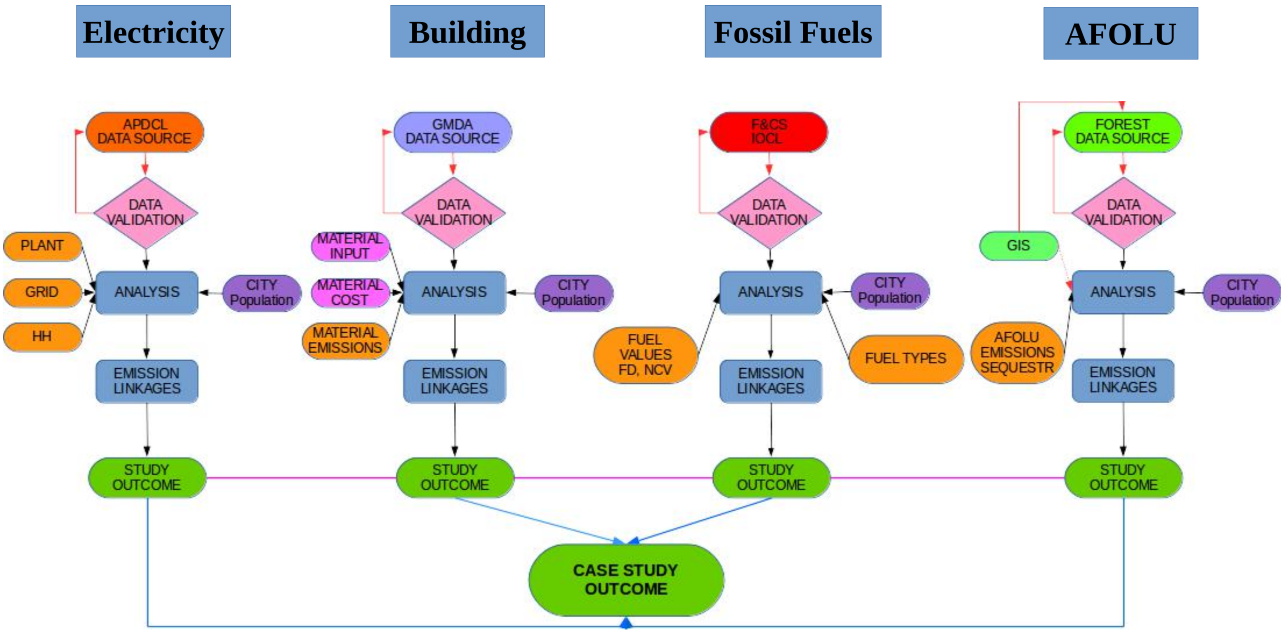

Fig. No. 3.3: The Case Study Methodology Process Flow

CHAPTER 4

4 Relationship between Entropy and the Development Process

One of the most important ecological problems for mankind, therefore, is the relationship of the quality of life of one generation with another-more specifically, the distribution of mankind's dowry among all generations. Economics cannot even dream of handling this problem (NGR, 1975, p374)

4.1 Introduction

To answer part of the 1st Research Question “1 (a). *Is there a relationship between entropy and development process*? 1(b). *What is the relationship between entropy and development process?*”, an extensive literature review was conducted. It is seen in Chapter 1 that there is a strong linkage between energy, entropy and development process as the development process is dependent on intake of energy and matter, which get transformed through production and consumption processes of the economy, generating entropy[45] at the end of every such cycle that feeds the development process. Economic processes obey the thermodynamic laws and hence are entropic. Similarly, the development process, which is an improvement in Quality of Life (QoL), depends on various energy and matter conversion processes that are also thermodynamic, and hence entropic. Application of thermodynamics systems approach brings to fore energy and matter conservation, irreversibility, waste generation and accumulation at the end of each process cycle leading to scarcity of low entropy resources, and the perturbation that waste accumulation may induce in the larger earth system described briefly in Chapter 2. The present Chapter takes this discourse ahead in order to address the issues of growth and development and dwells further on the Research Question 1(b). This Chapter also forms the theoretical basis of understanding

45 Here Entropy represents all waste (especially waste heat and CO_2) generated in the economic process

the Research Question "2. *Can the relationship between entropy and development process be understood from sustainable development perspective*?" The Thesis attempts to establish, with the help of a case study on urbanization as a good case of a development process, that high energy consumption is linked to a better QoL, leading to rise in entropy posing challenges to sustainability and driving climate change. In a world that is rapidly moving towards urbanization, it is expected that more than 63 % of the world population would reside by 2040 in cities (IEA, 2016) providing a high QoL that would generate more entropy and negatively impact climate stability, which forms the basis of city case study presented in the next Chapter.

4.2 NGR's Energy and Economic Myths: From Earth System to Development Process

The Chapter 2 was primarily based on the theories of NGR (1971) that he propounded in his magnum opus The Entropy Law and the Economic Process. The Chapter ended with a theoretical framework of economic subsystem within the larger earth system, which in turn is a part of the still larger sun-earth-space universe. Taking the framework forward and applying certain learnings from another seminal work of NGR (1975) entitled Energy and Economic Myths, a set of premises has been developed which are presented below. The two great works of NGR combined together form the foundation in exploring a new economic growth agenda. The writings of NGR are so prophetic that he got the climate change premonition[46] way back in 1975 when he says (1975, p359) "*What we experience today is only a clear premonition of a trend which may become even more conspicuous in the distant future*". His criticism of a US strategy plan[47] as a "linear thinking" to support larger than twenty billion human population by increasing energy supplies proportionately, and that the fate of humanity cannot cross beyond the sun

46 The climate change word was coined in 1966, and gained currency only after United Nations Framework Convention on Climate Change (UNFCCC) came in existence in 1992.

47 Weinberg and Hammond in 1970 gave a plan of getting nuclear fuel to run 32000 nuclear breeder reactor at 4000 off-shore locations to supply energy for twenty billion population for a million years with twice the then per capita energy consumption rates. NGR termed it as a grand plan of linear thinking (NGR, 1975, p370)

becoming a red giant[48], and all the reserves of fossil fuels on the earth would suffice only to light the globe for two weeks[49], go a long way to suggest the extreme depths to which NGR went to study the earth system from thermodynamic perspective. He says "*Since Entropy Law allows no way to cool a continuously heated planet, thermal pollution could prove to be a more crucial obstacle to growth than the finiteness of accessible resources*" (NGR, 1975, p358).

Premise 1: The earth system is a closed system, but unlimited supply of solar energy can enter the system. However, all energy that the earth receives must be thrown back to space lest the system gets either hot or cold. The sum of energy received and emitted by the earth system must be zero.

Premise 2: The earth system is a closed system, and hence its mass is fixed. The mass can only be transformed from one form to another, including forms of energy and waste (a form of material which cannot be used in any given process and level of technology). Unless mass is converted into energy using $E=MC^2$ principle, total mass after a process would remain the same as before the process.

Premise 3: Living organisms, including humans (as *Homo sapiens*), within the earth system can grow and multiply sustainably (as long as the earth system itself survives) harvesting the solar input energy provided the waste generated (including GHG and waste heat) do not alter the environment considerably. However, if the population growth rates are not controlled, resource exhaustion would lead to extinction of species.

Premise 4: Humans (as *Homo economicus*) can grow economically only till such time that resources within the earth system continue to flow in the economic process without getting

48 The sun is left with a life of another ~5 billion years, and has exhausted half of its fuel, at the end of which it would become a red giant (Mojsis, 2001). The earth would fall, at that point of time in the solar envelope and would be destroyed (Vila, 1984)

49 NGR estimated 215+200=415 Q units (1 Q unit=1.0550559×10^{21}J) to be the reserve of fossil fuels, while 5300 Q units of energy is received daily at the top of the earth's atmosphere. This gives a value of about 13 days energy to last. According to NGR, the annual consumption of world's energy is only 0.2 Q annually; while plants use 1.2 Q in photosynthesis

assimilated in biosphere as waste, and any such wastes do not alter the environment considerably. In the finite earth system, even zero growth[50] cannot exist for ever. However, growth in other dimensions (say energy, governance and spirituality) can continue without material growth subject to conditions of Premise 3.

Premise 5: Humans (as *Homo economicus*) need to look for new processes that are low in entropy by virtue of operating as close to normal temperatures and pressures[51] (say bio & nano technological processes) as possible, which would lead to low waste heat generation, and low in carbon leading to near zero CO_2 emissions.

Based on the above premises, the discussion has been carried forward in this Chapter which culminates in presenting an Entropic Framework of Sustainable Development based on the principles of NGR as propounded in the Entropy Law and Economic Process and the Energy and Economic Myths. The driver of the proposed sustainable development framework is “new processes” (NGR, 1971, p275) which are based on low entropy. With rapid pace of development and use of energy, there is no more a simple equation between science, economic growth and progress, and a new epistemology is required for science, life processes and development (Funtowicz & O’Connor, 1999). Thus, the task at hand is very challenging.

4.3 The Economic Growth and Development Paradox: Need for Degrowth

Economic growth has been defined as an increase in production of goods and services by an economy in a given time period, which is taken to be annual. The increase is normally measured in Gross Domestic Product (GDP)[52] of a country or a region. While doing so, it is important to distinguish between increase in GDP due to increase in the volume of the goods and services,

50 Zero growth economies are stagnant economies in which certain proportion of the stock capital (in words of NGR, Fund Flow) is written off and replaced by new investment requiring new skills (Rosenbaum, 2014). Zero growth economy models may be stable models with higher wage share profits, but less stable employment rate, when compared with an economy growing at 2% (Barrett, 2017)

51 T=298.15 K, P=1 atm, also called standard temperature & pressure (Atkins & Paula, 2010)

52 GDP is the value of goods and services produced within a territory or a country (*made in India*).

which is called "real GDP", and an increase due to rise in prices, which is called "nominal GDP" (Victor, 2015). NGR defines growth as increase in production per capita of current types of commodities which is measured by GNP[53] per capita at constant prices, and is linked with "growing depletion" of resources. On the other hand, according to NGR, development means introduction of innovations[54]. Growth and development are related to each other, as seen in the past, development induces growth, and growth occurs only in association with development (NGR, 1975). Development[55] can also be thought of as the central organizing principle of our socio-economic life in which the conditions that characterize the industrialized nations are on way for replication in the areas which are untouched by industrialization and termed as "under-developed" (Escobar, 2015). According to Gilbert Rist (1997), the definition of development, which he calls "scandalous" is "the general transformation and destruction of the natural environment and of social relations in order to increase the production of commodities (goods and services) geared, by means of market exchange, to effective demand." Rist (2007) sees development as an opportunity to convert almost anything into commodity for profit; and that the reverse side of production is the destruction of natural environment; lesser the number of free things available from nature, the more developed the country is.

GDP has been the most widely accepted measure of a country's economic growth. However, the basic question remains unanswered, "*Why does one do an economic activity, in the first place*?" Various attempts have been made to answer this question. At one end of the spectrum is John Stuart Mill's human being who "desires to possess wealth", and at the other end is NGR's human being whose purpose is "enjoyment of life". Without "*purposive activity* and *enjoyment of life*"

53 Gross National Product (GNP) is the total value of products and services produced in a given period by the means of production owned by a country's residents regardless of where the income came from (say *by Indians*). GNP is obtained by adding to GDP the income from abroad (PIDS, 2006)

54 NGR identifies three broad categories of innovations for analysis purposes: A. economy-innovations (to achieve an economy of net low entropy); B. substitution-innovation (physico-chemical energy for human energy); C. spectrum-innovation (new consumer goods)

55 Economic development, with its social and institutional correlates came to the forefront post World War 2. Development economics in its modern form did not exist before the 1940's" (Harris 2000).

no one can be in the economic world (NGR, 1971). Costanza et al (2009) have criticized inappropriate use of GDP as a measure of national well-being, something for which it was never designed, and also argue that economic growth is not always synonymous with improved well-being. Development is qualitative improvement in non-physical characteristics, while growth is quantitative increase in physical dimensions. An economy can therefore develop without growing, just as the planet Earth has developed (evolved) without growing (Daly, 1985). Development has also been seen as increasing Quality of Life (QoL) but not necessarily increased GNP or even "greened" GNP. Thus, development cannot be made synonymous with economic growth. The economy needs to be dematerialized to overcome the challenges of source and sink limitations (Gallopin 2003). The economic and development process both depend upon the transformation of matter and energy. This transformation is brought about by physical and chemical changes (NGR, 1971). Economic growth is directly linked to waste generation which affects QoL, and hence can be seen as degrading QoL in the long run by degrading the ecosystem services, while development is about increased QoL. Therefore, the above definitions of growth and development make them opposing to each other. **This is the paradox of growth and development**. Neoclassical growth models, thus, are in direct conflict with development (Daly, 1985). While most countries of the world have made significant advances both in GDP and in Human Development Index (HDI) measures, the approach is open to two pronged criticism, firstly that the benefits of development have been distributed unevenly, with income inequalities and secondly, that there have been major negative impacts of development on the environment and on existing social structures (Norgaard, 1994). Another major criticism of development has been the north-south divide between the countries of the world. Wealth differentials between developed and developing countries, rather than decreasing, have increased (Chichilnisky, 2001). The average per capita income of OECD countries is about sixty times greater than that of the roughly fifty low income economies (Mejia, 2010). Another criticism of the growth and development measurements has been the lack of accounting for the environmental damages caused by the economy. The Genuine Progress Index (GPI) subtracts social and environmental costs from GNP. When seen from GPI perspective, it is found that well-being has been decreasing in USA since 1980s (Bonaiuti, 2008). Quality of Life (QoL) and well-being are often used interchangeably in literature. Welfare is seen as social welfare and is measured using GDP. (Rokicka, 2013). Quality of life is about individuals' subjective assessment of their lives, while well-being is about objective conditions of life that apply generally to a population (Smith, 1973). QoL can also be called subjective well-being (Rokicka, 2013). While these definitions talk of QoL of the present generation, NGR talked of inter-generational QoL as the most important ecological problem for mankind (NGR, 1975).

4.3.1 Endosomatic – Exosomatic Instruments and Technological Paradox

Alfred Lotka, pointed on the crucial difference between man's entropic struggle and that of other living creatures. Alfred Lotka calls the organs of living beings as *endosomatic* instruments, while the equipment developed by man and other animals as exosomatic instruments, which according to NGR (1971) is more enlightening. According to NGR, "Exosomatic instruments not being a natural, indissoluble property of the individual person, the advantage derived from their perfection became the basis of inequality between the various members of the human species as well between different communities." Exosomatic instruments which mean better and bigger equipment have helped man to move towards a better, comfortable and safe life, have more economic growth and development, and cause more environmental damage. Therefore, exosomaticism is about improvement in technology. Issues have been raised whether technology can overcome every limitation that would arise in future, and whether such a technology would reduce the impact on the ecosystem (Bonaiuti, 2008). However, the limitations of technology need to be addressed. The question to be asked at this point is "Can technological progress overcome resource scarcity and assimilation limits of the sink?" or in other words, can we address the Rebound Effect- Jevons' Paradox[56]?

4.3.2 Sustainable Development[57]: Sustainable or not?

NGR (1975) talks of "Quality of Life of one generation with another" as most important problem of mankind, and in doing so provides the most comprehensive definition of sustainable development. Daly (1996) argues "Sustainable development is a term widely used by politicians and scholars all over the world, even though the notion lacks a uniform interpretation. *Sustainable development is a term that every one likes and nobody is sure of what is means- at least it sounds better than unsustainable non development*". Development is sustainable if it "meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNCED, 1987). World bank perceives "Sustainable" development "equitable and balanced" development which is is about equity, and results in eradicating extreme poverty. (Soubbotina, 2004). Dasgupta (1994) defines sustainable development as development that maximizes the total (discounted) welfare of current and future generations, taking into account, not only the constraints imposed by the fitness of natural resources, but also all the possibilities for technological substitution between different kinds of capital goods, be they physical, natural, or intellectual. As can be seen from the various definitions and view points, barring that of Daly, these are most ideal visionary constructs which have no meeting point on the horizon. Daly (1996) says that sustainable development is development without growth, and it means "living

56 Jevons' Paradox (Rebound Effect), named after William Stanley Jevons (1835-1882), states that technological change that increases the efficiency of resource use, increases the rate of consumption of that resource instead of decreasing it (Alcott, 2015). The paradox was originally proven by Jevons (1865) for coal, but now proven true for other resources as well. For example, doubling the efficiency of food production per hectare due to the Green Revolution, instead of solving the problem of hunger, worsened it due to increase in production leading to resulting increase in population (Mayumi, 2009)

57 Sustainable development has also been termed as an "Oxymoron" (Brown, 2015), just as "sustainable city" has been termed as an Oxymoron (Rees, 1997)

within environmental constraints of absorptive and regenerative capacities". He further says that the constraints on sustainable development are both local (soil erosion, deforestation etc.) as well as global (global warming, ozone hole, disruption in natural cycles etc.). According to Costanza (2008), there are four basic capitals[58] that are necessary to support the real, well being-producing economy. These are Built capital, Human Capital, Social Capital and Natural Capital. The market economy takes into account mainly the built capital, part of human capital (spending on labour, health and education) with some limited spill over into social and natural capital. Daly (2005) talks of two capitals namely natural and man-made, and NCE believe that man-made capital is a good substitute for natural capital, advocating maintaining a sum of the two. This approach is called ***"weak sustainability".*** The opposing view is termed as ***strong sustainability.*** Taking the example from fishing industry, the annual fish catch, which is limited by the natural capital of fish populations in the sea would follow weak sustainability framework if the lack of fish is dealt with by building more fishing boats, and strong sustainability if realized that more fishing boats are useless and catches must be limited to ensure maintenance of adequate fish populations for tomorrow's fishers (Daly, 2005). The approach taken by NGR is that of the strong sustainability, as he questioned the substitutability approach of the neoclassical economists. With the above background on sustainable development, it is important now to turn to NGR's views on sustainable development.

4.3.3 NGR's Sustainable Development Snake Oil Revisited

In a letter to Kozo Mayumi in 1992, NGR describes sustainable development as snake oil[59]. In

58 **Built capital** is man made capital and includes infrastructure such as factories, offices and other built infrastructure and their products. **Human capital** includes the health, knowledge, and other attributes of individuals that allow them to function in a complex society. **Social capital** includes the formal and informal networks among people: family, friends, neighbours, social institutions at all levels such as churches and clubs, NGOs, governments and national and international bodies. **The natural capital** includes the world's ecosystem and all the services that they provide. Eco system services occur at many scales, from climate regulation at the global scale, to flood protection, soil formation, nutrient cycling, recreation and aesthetic services t local and regional scales

59 Snake Oil as an industry run by quacks survived 150 years in USA. It denotes a false promise.

another correspondence to J. Berry in 1991, he calls it "a more beguiling snake oil than the steady state" (Bonaiuti, 2011). The criticism of sustainable development by NGR was not taken note of, as the word was catching fancy of one and all. John Pezzy of World Bank is said to have counted 37 different definitions of it by 1989 when the definition first came up in 1987, and the debate just started. NGR criticism of sustainable development was revived a decade later by Bonaiuti (2001) and Latouche (2004) when the degrowth debate started. The snake oil analogy of NGR is very apt for sustainable development. Arguing that Quality of Life of one generation cannot be handed over to another, and taking the example of coal, NGR (1975, p374-375) demonstrated that just allocation of resources and market mechanisms cannot ensure availability of coal beyond a few generations. In the words of NGR "*Economics cannot even dream of handling this problem*". The fallacies can be understood from Fig No. 3.1. As discussed, economic and development processes are entropic in nature. Further, improvements in technology and efficiencies get under the Jevons' Paradox and create a positive feedback loop in the economy causing more pollution and waste and resource depletion.

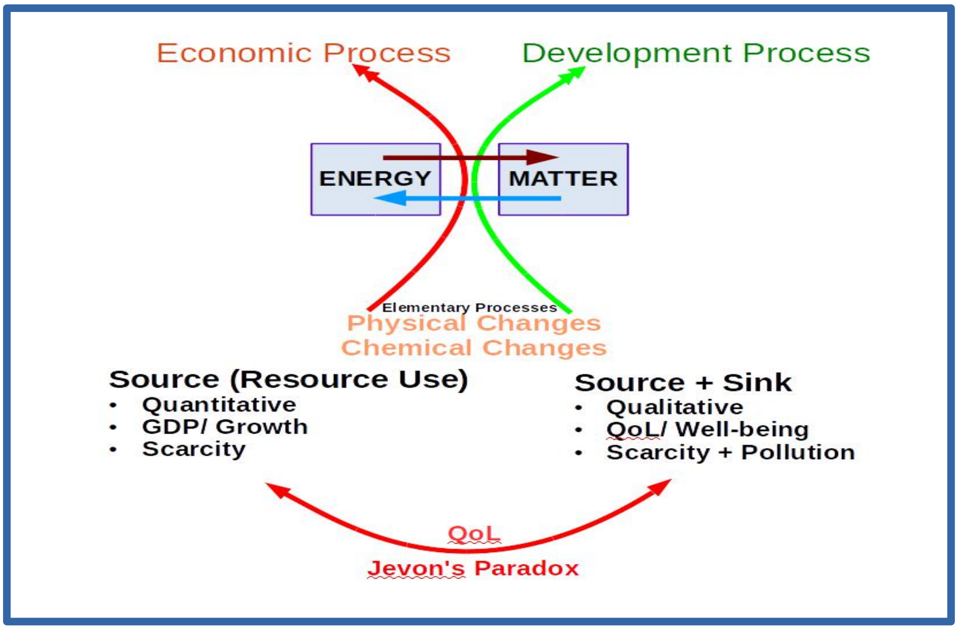

Fig. No. 4.1: A Schematic of Economic & Development Process (Author's Illustration)

On sink side, the CO_2 level which was 300 ppm in 1896 (when Svante Arrhenius gave the Green House Effect Theory in 1895) is now 409 ppm in May, 2017. On the source side, while “peak oil” is a common concern of all, scarce elements such as phosphorus (needed for most biological processes) do not get the same attention. However, NGR talked of phosphorus crisis way back in 1975 which went unnoticed. Now “peak phosphorus” crisis is fast approaching. Given the entropic nature of energy and matter, and the existing transformation processes, NGR predicted, that what to talk of sustainable development, even steady state and zero growth are fallacies (NGR, 1975, Bonaiuti, 2011, Martnez-Alier, 2012, Gorz, 1980). Will the snake oil era be over ever?

4.3.4 Economy, Energy, Environment: The Climate Stability Challenge

Human beings first learnt to manipulate fire about 500,000 years ago. The neolithic revolution brought about the first transformational change in the human race when the hunters and gatherers[60] settled and turned to agriculture, whose energy system centred around natural energy sources of sunlight, animal and human muscle power to get heat, light and work. These societies depended on animal energy flows of about 8 to 15 kWh a day of energy which translates to about 10-10 GJ per year per capita. Energy use in the initial stage of hunter gatherer was limited to body energy. The pastoral stage saw harvesting of solar energy (in growing crops) and animal energy (rearing beasts of burden and cattle), and negligible amounts of fossil fuels (GEA, 2012). *This era has been termed as Organic Energy Economy. This has also been termed as somatic energy regime with “endosomatic metabolism” and also called as agrarian metabolic regime of which “biomass consumption” was the predominant element (Bithas and Kalimeris, 2016).* The industrial revolution, symbolized by the steam engine, signaled the start of “Fossil Fuel Economy”. NGR considers fire, agriculture and steam engines as Promethean[61] innovations. By

60 NGR called it “berry picking economy” (NGR, 1975, p367)
61 Promethus, a Titan, is credited with bringing fire back from heavens and giving it to man.

1800 only 0.35 EJ of coal energy was used, which rose to 20.62 EJ by 1900, and 87.83 EJ by 2000. Crude oil consumption started in 1870 with 0.02 EJ, and it rose to 0.65 EJ in 1900 and 129.02 in 2000. Natural gas consumption started in 1890 with 0.12 EJ, and it became 0.23 EJ in 1900, 86.46 EJ in 2000 (Smil, 2010). For the western countries it was estimated that GDP per capita rose from US$ 1240 in 1820 to US$ 3350 in 1900 and US$ 26000 in 2006 (at constant prices of 1990)[62]. There is overall positive correlation between energy and economic growth. A study (Karanfil & Li, 2014) showed that 160 countries of the world had 96.52% of global GDP and 94.61% of global electricity consumption in 2010. It is projected that the economy would grow by 88% from 2013 to 2030 and energy-related CO_2 emissions would grow by 8% reaching a value of 34.8 $GtCO_2$.(IEA, 2015).

4.4 The New Growth and Development Paradigms: Emerging Trends

The snake oil effect may be gotten better of only if the Business As usual (BAU) pathways are abandoned. The BAU trajectory of the economic growth would lead to 3.5^0 C rise in the mean global surface temperature by the end of this century triggering catastrophe of climate change, including sea level rise, ocean acidification, extreme storms, droughts, floods, crop failures, and the collapse of whole ecosystems (World Bank 2012). The world per capita CO_2 emission stood at 4.9 tCO_2 per capita in 2011 which must be brought down to 2 tCO_2 per capita by 2050 (EDGAR, 2013, Stern, 2008). These concerns bring us to the the concepts of environmental thresholds, ecological and biophysical limits to economic growth that have been put forward by scientists from different fields in the last two decades. Some of these approaches are Gaia

62 Charles I. Jones, 2015 (http://www.hoover.org/sites/default/files/jones-facts040.pdf)

Hypothesis[63] (Watson and Lovelock, 1983), the Natural Step[64] by Dr. Karl-Henrik Robert (2002), Planetary boundaries[65] by Johan Rockstrom ((Rockström et al 2009), Blue Economy[66] by Guntur Pauli (2010), Planet under Pressure Conference and the State of Planet Declaration[67] (PUPC, 2012).

Prelude to Degrowth- the North-South Dilemma: As already discussed, development process as we understand today is that of the developed and industrialized countries (*North*) that have very high per capita consumption of energy and matter. In terms of the entropic definition of development used in this Thesis, the concept can be reduced to a *simple representation* (see Fig No. 4.3) of energy matter transformation (denoted by a function $\mathscr{F}$) where the goods and

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63 The Gaia hypothesis, also known as Gaia theory or Gaia principle, proposes that all organisms and their inorganic surroundings on Earth are closely integrated to form a single and self-regulating complex system, maintaining the conditions for life on the planet. The abiotic environment and the biotic environment interact together to influence the Darwinian evolution of biota (Watson and Lovelock, 1983). Lovelock combines biology and geoclimatology to form one science which he calls geophysiology- the study of living and non living in the earth system. Lovelock argues that in order to maintain the earth system's current thermodynamic and chemical state of *homeostasis* life on earth is necessary, until some external force interrupts it, at which point the system would move to a new stable state

64 Dr Karl-Henrik Robert developed the *Natural Step approach* in Norway in the 1980s. In 1991 he attempted to establish linkages between the basic environmental laws and sustainable society. Based on scientific consensus of what was required to maintain the earth's systems, the approach focused on what were called `system conditions' and these became the primary focus of the Natural Step approach. The Natural Step emphasizes that the only long term sustainable approach in which business and society can operate is within the earth's natural cycles. The scientific principles that it follows are 1st and 2nd Laws of thermodynamics; and that net increases in material quality on earth can be produced by sun driven processes (Karl-Henrik, 2002).

65 Nine planetary boundaries were suggested by Johan Rockstrom. These concern various global system issues including climate change, biodiversity loss, nitrogen and phosphorus cycles, freshwater use, land system change, ocean acidification, stratospheric ozone depletion, chemical pollution and aerosol loading. Planetary boundaries provide a powerful description of the global “adding-up” constraints across key dimensions and outline safe operating limits for humanity to minimize the likelihood of harming the Earth system beyond the limit that threatens economic growth. (Rockström et al 2009).

66 The Blue Economy is a new economic growth and production paradigm developed and promoted by Gunter Pauli. He believes strongly that the factories of nature produce high quality material at very low cost mainly because the natural operations mostly take place at standard temperature and pressures in contrast to the normal economic production process operating at high temperatures and high pressures causing high entropy change in the surroundings. He also very strongly believes in recycle, reuse and reduce. He has successfully set up business across the globe based on the blue economy principles with great success.

67 The Planet Under Pressure Conference held in London in the year 2012, organized by the Global Change Research Program of the International Council for Science came up with the State of the Planet Declaration which brought together about 3000 experts and decision makers to discuss global challenges and offer new solutions. The Conference laid emphasis on urgent action to counter threats of scarcity of natural resources, loss of biodiversity, while human impact on the earth system was becoming comparable to planetary scale geological processes, and the planet is pushed to a new age called Anthropocene (in which human activity controls *Earth-system processes and the living fabric of ecosystems). The Conference was of the opinion that though rapid scientific and technological progress could provide potential solutions to reduce the risk of deleterious consequences, but technological innovation alone would not suffice, and there is a need to “transform our values, beliefs and aspirations towards sustainable prosperity”*

services (G&S) are wholly dependent upon energy (E) & matter (M). The more a population develops, the more entropy would it generate and create resource crisis on the source side. This is the "development" of the west, which if the rest of the world (*South*) were to adopt, may lead to the collapse of the planet. *However, while the North "developed", can the South be denied that "development"?*

$$\begin{aligned}\text{Development Process} &= \mathscr{F}\,(\text{QoL}) = \mathscr{F}(\text{Energy, Life Style, Status})\\ &= \mathscr{F}\,(\text{Economic Processes})\\ &= \mathscr{F}\,(P_n, C_n, B_n, \ldots)\\ &= \mathscr{F}[P_n(E, M), C_n(E, M), B_n(E, M), \ldots]\end{aligned}$$

$$\Sigma E_{INPUT} = \Sigma E_{OUTPUT} + \Sigma\Delta E$$

$$\Sigma M_{INPUT} = \Sigma M_{OUTPUT} + \Sigma\Delta M$$

$$G\&S = \mathscr{F}_o(E_{OUTPUT}, M_{OUTPUT}) = \mathscr{F}_i(E_{INPUT}, M_{INPUT})$$

Fig. No. 4.2: Energy-Matter Representation of "Development" Process (Author's illustration)

Degrowth- : Degrowth[68] movement has its origin, geographically in Europe, and its inspirational roots in ecological economics and can be traced to NGR. A selection of his writings was translated into French by Grinevald and Rens in 1979 under the title "*Demain la decroissance*" (Martinez-Alier, 2012). Environmental justice and degrowth are closely linked. The environmental justice organizations (EJO) supporting the degrowth movement are espousing the notions of Buen Vivir (collective well being) and the Rights of Nature (Martinez-Alier, 2012, Escobar, 2015). However, these debates are also bringing to fore the chasm of development between the North and South. The era of development of the North is coming to an end, and new alternatives of development i.e. degrowth. While degrowth is receiving much attention in the North and has entered the political debate, while in the South its not the case. Degrowth has two aspects which merit attention here. Firstly, whether North or South, certain sectors need to grow

68 See Foot Note 15

as the populations grow, especially health, education and livelihoods. Secondly, while the North needs to "degrow", the South has a strong requirement to "develop". The question is whether "development" is what defined the material and energy trajectory of the North, or is a new development paradigm (Escobar, 2015). While degrowth is gaining ground, sustainable development, though a snake oil, is still very popular in all debates where growth and development are talked of, especially in the context of ecology and the biosphere. *Could it be that sustainable development be the end and degrowth the means*?

4.5 The Entropic Framework of Sustainable Development: From Snake Oil to Sustainability

It was not without reason that NGR called sustainable development snake oil, which has already been discussed earlier in this Chapter. However, by giving an entropic perspective to it, sustainable development can be grounded in the real biophysical world, where irreversibility rules and source and sink capacities limit growth. Referring back to NGR, we see that he also holds the key to sustainability. He talks of a "take-off" economy when "*essence of development consists of the organizational and flexible power to create **newer processes** rather than the power to produce commodities by materially crystallized plants*" (NGR, 1971, p275). Thus, "**New Process**" is the central concept that could drive sustainability and remove the snake oil tag of sustainable development. The premises described at the beginning of the Chapter have the foundational elements to build an entropic perspective to sustainable development. The components of the new framework are explained briefly:

New Process: The new processes are of two types, 1. processes that are economic in nature and should operate at lower temperatures (T↓) and pressures (P↓) preferably close to normal temperature and pressure, with increased efficiencies (*h*↑), and incorporating 3R/4R, and thus are essentially technological; 2. processes that are non economic and non technological such as policy interventions and life styles. While economic processes are driven by non economic processes such as "green" & "low carbon" policies, they, in turn, drive the new elementary physical and chemical processes (low entropy) in production, distribution, consumption and reduction based on 3R principles. Plenty of such processes have been successfully demonstrated by Gunter Pauli (2010), all of which are "zero waste" connected processes, just as we find in nature. New processes would build new economies that would drive new life styles and well being, and strive at creating zero waste societies. Further, temperature would be most crucial factor in the new processes that would be designed in future. Similarly, the non economic processes that would govern policies, life styles and well being would need to be viewed from a totally different perspective- what is considered "developed" today would start appearing very backward tomorrow. With the current definition of development in vogue, we shall continue to be living in the era of snake oil of sustainable development, and forced to revert back to "berry picking economy" that NGR predicted.

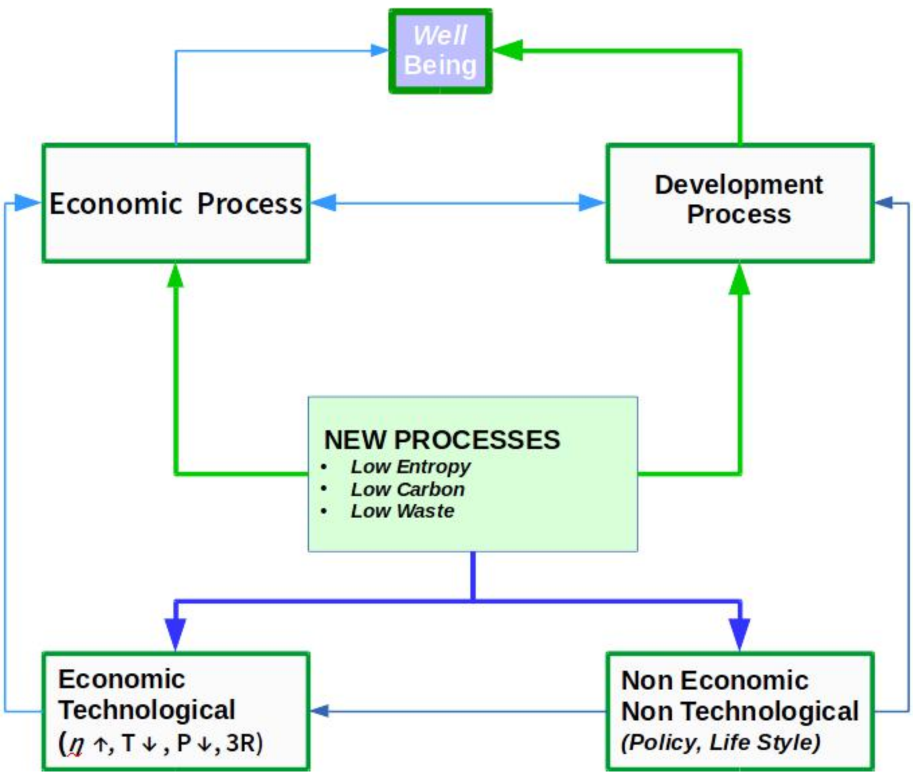

Fig. No. 4.3: An Entropic Framework of Sustainable Development

New Economy: The present day dilemma is "To grow or not to grow?". If we purse growth, the earth ecosystem gets endangered; and if we retard the pace of growth, it may lead to economic and social collapse. It is necessary to revise the ecological and social conditions of production of wealth (Jackson, 2015, Bonaiuti,2008). Some western economies have dematerialized by reducing heavy manufacturing and importing consumption goods from other countries, but it cannot be a good model. One needs to look at reduction in resource intensity, but the throughput of a 7.2 billion population projected to grow to 9 billion can tip the scales against resources as well as sink assimilation. On the other hand, unequal societies undermine well-being. A sustainable economic framework essentially should ensure economic activity within ecological limits, the working principles should be coded with the limits if a finite planet, the natural resources must be well accounted for in the System of National Accounts (Jackson, 2015).

Well-being: Well-being is social in nature and applies to a population as opposed to an individual, and is a higher goal than Quality of Life which is subjective and individualistic (Smith 1973, Rokicka, 2013). Life style changes driven by well-being *are an effective and powerful approach to addressing sustainability issues, as they can provide multiple benefits like improved health, low fossil fuel based mobility, lower emissions, and nutrition, without reducing socio-economic status (Roy et al, 2012).* QoL has a strong connotation with life style in industrialized nations (aspiring to western lifestyles), and hence promotes high per capita energy, high per capita CO_2, and high per capita material resource. On the contrary, well-being connotes well with "zero carbon" and "low entropy" growth. It is the "common weal" - "*Sarve bhavantu sukhinah, sarve santu niramayah, sarve bhadrani pashyantu, maa kaschit dukh-bhag bhawet*"[69] - of the society. NGR talked of enjoyment of life which was the real output of an economic process. A good measure of well-being would be Happy Planet Index[70]. Topping the Happy

69 Ancient Sanskrit Shloka meaning "*May all become happy, may all be free from illness, may all see what is auspicious, May no one suffer*"
70 http://www.happyplanetindex.org

Planet Index rankings for the third time, Costa Rica has shown that their citizens have higher wellbeing than the residents of many rich nations, including the USA and the UK, and higher longevity than even the people in the USA. The country is having a per capita Ecological Footprint that's just one third of the size of the USA's, and it uses 99% of electricity from renewable sources 13 and the government is far ahead of many wealthier nations, having committed the country to becoming carbon neutral by 2021.

A New Sustainable Development Framework: At the root of the new sustainable development framework is the concept of "new processes" which are low carbon, low entropy and "dematerialized", such as "Blue Economy" (Pauli Gunter, 2010) or "Permaculture" (Mollison & Holmgren, 1978) accompanied by a set of policy drivers, such as NGR's "minimum bioeconomic program" (NGR, 1975), or "natural step" (Cook, 2004). The low entropy processes which operate at close to normal temperature and pressure, and have little or no carbon footprint, drive the new economic growth and development. On the other hand, the new policy stacks drive the economic as well as the development agenda. Since, the ultimate aim is to achieve social well-being, which cannot be achieved in absence of the new low energy, low entropy and low carbon driven processes, it is fed by the "right" kind of economic and development processes backed by a conscious societal policy framework and technology. This framework meets all the requirements of NGR's growth and development ideology as set in the Entropy Law and Economic Process (NGR, 1971) and the Entropy and Economic Myth (NGR, 1975), and is derived (though qualitatively) from thermodynamic considerations and the theoretical framework developed in Chapter 2, and the five premises given at the beginning of this Chapter. Instead of economic enterprises, let there be ecological-economic enterprises that follow the four principles:

1. Strive for lowest possible resource intensity and entropy footprint
2. The output promotes well being, does least harm environment
3. Account for all natural resources consumed, ecosystem services availed and environmental damage caused
4. Gives back to the environment what is taken from there or repairs what is damaged

Entropy (waste heat and CO_2 emission) could very well serve as an excellent indicator of sustainable development framework proposed above, as well as be a direct single measure the damages a process may cause to the environment, and thus induce climate change. An attempt has been made partially to apply the above framework, in coming up with a single entropy value of the outcome of a development process by taking the case urbanization. A perspective on urbanization is presented in the sections that follow.

4.6 Why Urbanization as a Case? The Energy Use Paradox:

Urbanization is a development process that has huge impact on resource use and environmental degradation. The energy and matter resource are the essential inputs required for the development process. The quantum of waste generation and conversion of natural resources by the urban growth engine into a state of used-up energy and matter is rapidly increasing. The entropic nature of energy and matter is leading to scarcity of resources and filling up of sinks manifesting itself in the form of climate change. There are several important aspects to the issue at hand, with global and local ramifications. Some of these are briefly examined below to establish the need for the study.

In 2014, 53% of the world population, amounting to 3.84 billion, lived in urban areas. There have been two waves of urbanization the past, namely the first urbanization wave took place in North America and Europe over two centuries from 1750 to 1950. The urban areas have increased from 10% to 52% with an urban population of 423 million. The second wave of urbanization in the less developed regions such as Asia would cross 3.9 billion in 2030. During this period from 1950 to 2030, these countries would witness rise in human population to 3.9 billion. (UNFPA, 2007). In 1950, 30% of the population lived in urban areas, which has increased to 47% in the year 2000 and is expected to increase to 60% by the year 2030. From 2000-2030, virtually all population growth is expected in urban areas and mostly in less developed regions of the world (UN, 2002). Between 2000 and 2030, Asia's urban population will increase from 1.36 billion to 2.64 billion. (UNFPA, 2007). The urbanization and population trends for select regions of the world is given below for 2014 and 2040 (IEA, 2016):

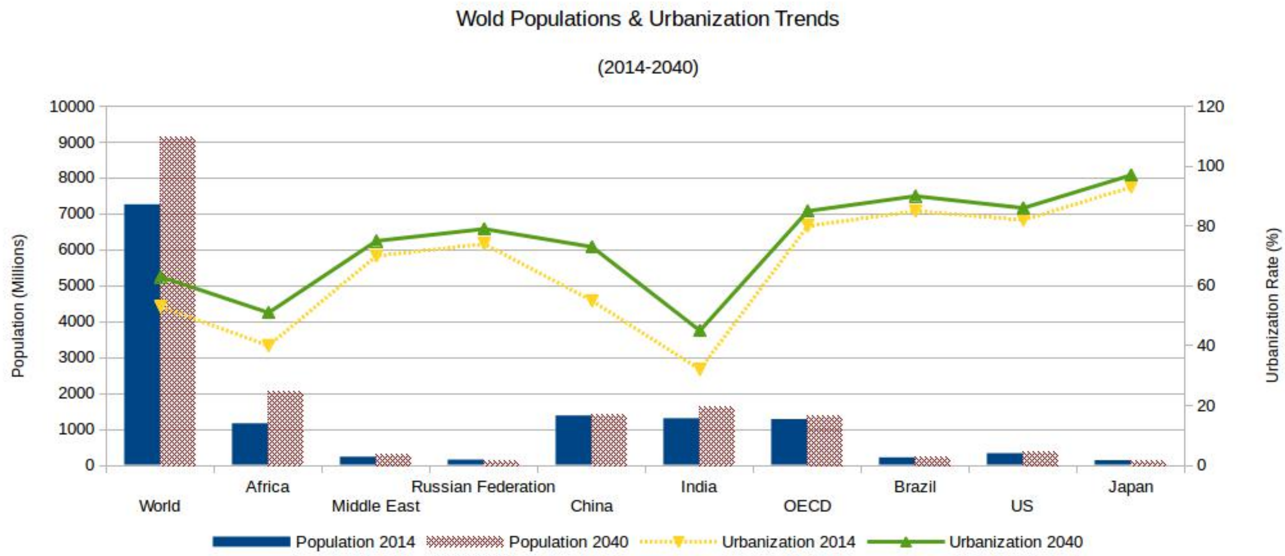

Chart No. 4.1: World Populations and Urbanization

4.7 Urban Energy Use and Climate Change

Energy is the main propeller of high living standards in a city. Improvement in life styles is directly linked to the per capita energy usage. Sunita Narain et al (2009) assert that human development by any country in the world is not possible without corresponding increase in per capita use of energy. The world per capita electricity usage comes to 15000 kWh, that of China is

4000 kWh. India's per capita electricity usage was 914.41 kWh in 2012-13, 957 in 2013-14 and 1010 kWh in 2014-15. The per capita wattage for the world comes to 1712 W, for China the figure is 457 W and for India, it is 115 W. The GDP and per capita power consumption of select economies of the World is given in Fig. No. 4.5 (data from IEA, 2016). Cities are responsible for 75% of global energy consumption and 80% GHG emissions (UN-HABITAT, 2007). Its also predicted that by 2040 63% of the world populations would live in cities (IEA, 2016). With sharp rise in urban populations already predicted, rise in energy consumption and emission levels are only corollaries. Cities would increase their order (negentropy) by increasing global entropy (Rees). However, cities can be sustainable and are also seen as solutions to GHG emissions (Moore et al, 2013, Dodman, 2009).

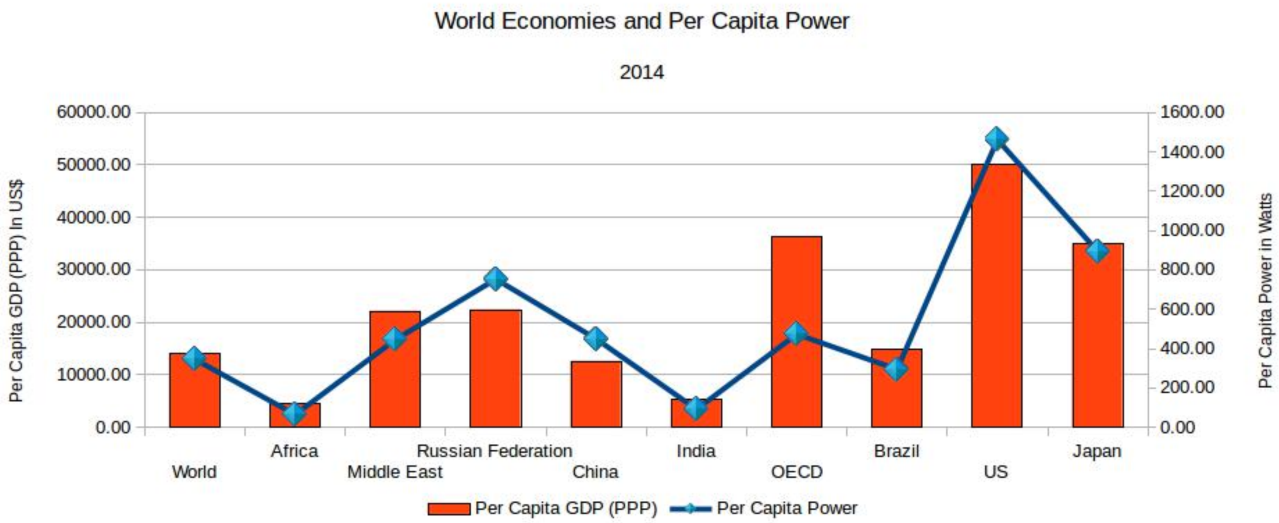

Chart No. 4.2: World Economies and Per Capita Power

International Energy Agency (IEA) estimated that the urban areas contributed 67% to the global primary energy demand and 71% energy-related CO_2 emissions for the year 2006. CO_2 is estimated to increase to 76% by 2030 (IEA, 2006). As urban populations grow, huge investments in infrastructure development would be required. It is estimated that physical capital investment of over 20 trillion USD by 2025 would be required in the emerging economies to meet this demand (OECD, 2014). IEA estimates that the cumulative needs in energy supply and in energy efficiency will reach USD 53 trillion by 2035 to get the world on a path to achieve 2^0 goal (IEA, 2014). Energy use and emissions are directly linked. Cities would hold the key in determining the journey to achieve the achieve 2^0 goal. The strategies should include electrification of vehicle transport, solar heating/cooling for buildings, CO_2 free electricity generation by 2050 using a mix of renewables (essentially wind, solar), nuclear and Carbon Capture and Storage (CCS) technologies, major energy efficiency gains across all sectors, advanced biofuels for transport and land use change and emission reduction in agriculture. On the other hand, urban authorities are largely unaware of the pressing need for efficient energy management and CO_2 reduction targets for their cities. Literature review has shown that there has been limited research on the management of energy within the cities. The studies were not considered important at the city level until recently, and most energy related decisions were made at the national levels. (IGES, 2004).

4.8 Urbanisation and Sustainable Development: The Problem or the Solution?

Urbanization is proceeding at a very rapid pace in all developing countries. Between today and 2050 the share of the world population living in urban areas is expected to rise from approximately 50 percent to around 67 percent. The scale and speed of this change is unprecedented in human history. China alone is expected to add some 250 million new urban citizens from 2010 to 2025. Global investments in urban infrastructure and building are expected to rise from $10 trillion today to more than $20 trillion by 2025, with urban centers in emerging economies attracting the most of this investment (Revi and Rosenzweig 2013). According to Rees, “Cities are dissipative structures which raise difficult questions as to whether cities can help to solve global sustainability challenges broadly related to energy use or whether they are root of the problem (Moore et al, 2013). Cities use more energy and therefore, emit more green house gases (GHGs). According to a World Bank study, “The link between economic growth, urbanization and green house gas emissions is by now accepted as a basis from which to start discussion alternatives. Because so much economic activity is concentrated in urban areas, urbanization and growth have a direct consequence on city green house gas emissions and related climate change. To promote growth and also to mitigate climate change impacts, cities will need to shift energy sources, improve energy efficiency and increase city density” (World Bank, 2010). However, the urban growth engine would continue to remain energy intensive. Though technological interventions would possibly find solutions to energy scarcity, the Second Law of Thermodynamics would always operate on the energy intensive economic processes that promise to improve quality of life. No doubt, continuous efforts are being made to reduce the negative impact of the green house gas emissions due to intensive energy use in the cities by focusing on green technologies, green buildings, clean technology etc., little effort has been made in the direction of meaningful entropy reduction other than efficiency enhancements. Sustainable development needs to be looked from the perspective of reduction in transformation of low entropy resources to high entropy waste.

4.9 Conclusion

The economic process that feeds the development process is entropic in nature. The discussion in this Chapter demonstrates that energy continues to be the driving force for development, and also contributes to climate change. Therefore, development is also entropic in nature. As would be demonstrated by the Case Study in Chapter 5, entropy correlates positively with growth parameters such as population growth. Sustainable development as understood commonly has been well criticized by NGR on the grounds that it cannot be sustained beyond a few generations. NGR is of the opinion that new processes need to be brought in which could enable economy to take off. The New Economy is also suggested where reducing the matter and energy is the key factor (Jackson, 2015). Based on this premise, an entropic framework of development has been proposed. To demonstrate that development is entropic, urbanization as a case of development was taken, and shown, through sectoral case analysis, presented in Chapter 5, that entropy increases with development posing a challenge to sustainable development on one hand and as a possible solution towards long term sustainability.

CHAPTER 5

5 City Case Study: Guwahati City

The true product of the economic process is an immaterial flux, the enjoyment of life, whose relation with the entropic transformation of matter-energy is still wrapped in mystery. (NGR, 1976, pxiv)

5.1 Introduction

This Chapter deals with the Case Study of Guwahati City as a development process and explores the energy and mass input and waste output (CO_2 & waste heat). The sectors comprise of electricity and fossil fuel[71] consumption, embodied energy in buildings, and AFOLU which comprises of forest to settlements, fuelwood, agriculture and wetlands. The sectoral studies namely: 1. Electricity, 2. Fossil fuels, 3. Building, and 4. AFOLU have been described individually with sector specific data sources, methods, findings, discussion and analysis. At the end, key findings have been summed up from all sectors, and the total and per capita entropy generation and CO_2 emission for the city have been worked out.

Structure of the Case Study: The Chapter is divided into three parts. **Part A** gives an introduction of Guwahati city its population and built up along with the city ecosystem in brief. **Part B** contains the Case Study methodology. **Part C** contains the sectoral studies. The sectors studied are depicted in the **Fig No. 5.1**.

71 Petrol (MS), High Speed Diesel (HSD), Kerosene (K/OIL) & LPG

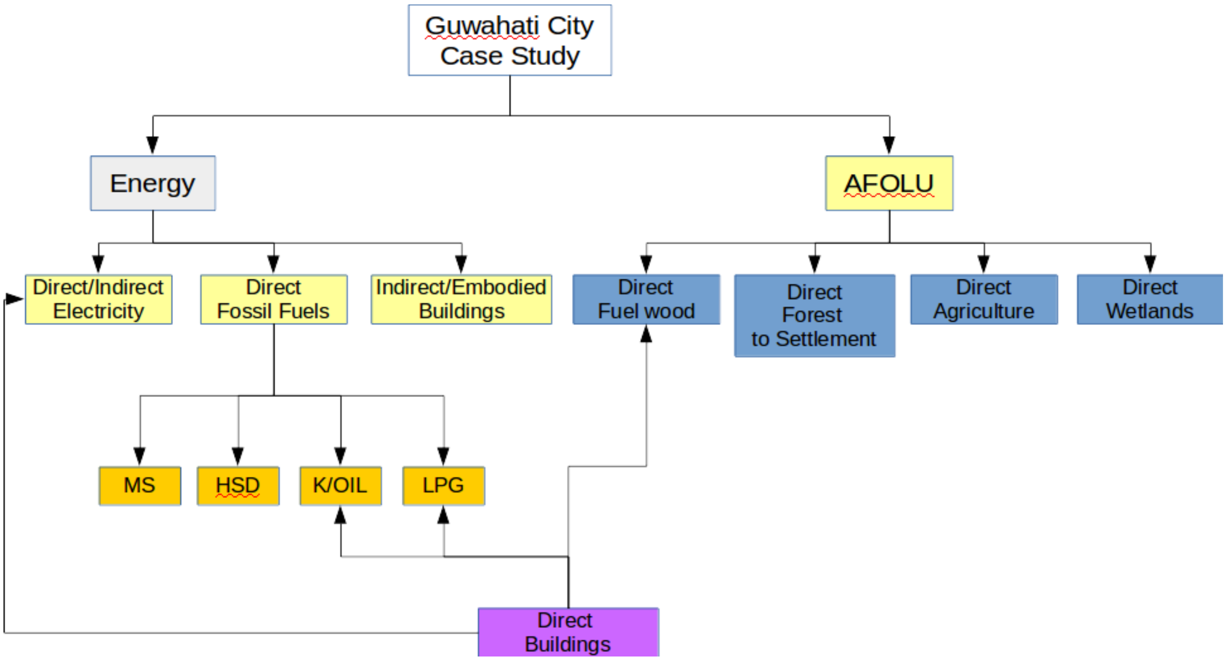

Fig No. 5.1: Sectors in Guwahati Case Study

PART A

5.2 Guwahati City: An Introduction

The study area comprises of Guwahati city which is located in the northeastern region of India and situated between 26^0 5' to 26^0 13' N latitude and 91^0 35' to 91^0 52' E longitude, on the banks of the river Brahmaputra[72]. For the study, area under the Guwahati Metropolitan Development Authority (GMDA)[73] was considered. GMDA's jurisdiction extends over an area of 262 sq. km. covering the entire Guwahati Municipal Corporation (GMC)[74] area, entire North Guwahati Town Committee area and some revenue villages of Silasundari Ghopa Mouza, Pub Barsar Mouza, Dakhin Rani Mouza, Ramcharani Mouza, Beltola Mouza. The city falls within the civil jurisdiction of Kamrup (Metro) district, which was a part of the erstwhile Kamrup District (GMDA 2009, Gogoi 2011). The location map of the study area is shown in **Map No. 5.1**

5.2.1 Topography of Guwahati

The topography of the city is undulating varying in elevation from 49.5m to 55.5m above Mean Sea Level (MSL). The land is interspersed with a large number of hills.. The central part of the city has small hillocks namely Sarania hill (193m), Nabagrah hill (217m), Nilanchal hill (193m) and Chunsali hill (293m) (GMDA Plan, 2009). The Agiathuri hill, and Maliata hill lie on the northern and western boundary of the city limits. The Buragosain Parbat in the East and the hills of Rani and Garbhanga in the south form the major hill formations of the city. These hills make contiguous formations with the hills of Meghalaya. There are total of 18 hills in the city. The total reported area covered by hills in GMDA area is 6881 Ha (Anon 2010). The hill tracts are mostly covered with forests. The hills within the GMDA area are shown in **Map No. 5.2**.

72 Brahmaputra River is one of the major rivers of Asia flowing through Tibet (China), India and Bangladesh having a length of 2900 km and having a basin area of 712,035 km^2.

73 GMDA was established in 1992 as per Guwahati Metropolitan Development Authority Act 1985. It replaced the erstwhile Guwahati Development Authority constituted in 1962 under the Town and Country Planning Act, 1959

74 GMC is the local urban body of Guwahati formed in 1971 by the Guwahati Municipal Corporation Act, 1969

5.2.2 The Forests of Guwahati

The hills are mostly covered, barring the rocky outcrops, with **forests** of various formations ranging from Sal forests, Mixed Moist Deciduous Forests, Evergreen Forest, Bamboo Brakes and Secondary Scrub Forests. The forests in and around the city fall under the Kamrup (East) Forest Division. The management of the forest tracts are carried out as per prescriptions of the Working Plans. As per the working plans, there are a total of 14 Reserved Forests (RF) within and on the immediate periphery of the city area. The total RF area comes to 33342.55 Ha comprising of Rani RF(1882, 4361.584 Ha), Maliata RF (1915, 324.776 Ha), Agiathuri Hill RF (1917, 363.196 Ha), Garbhanga RF (1926, 11441.28 Ha), Garbhanga 1st Addition (1990, 7395 Ha), Khanapara RF (1953, 994 Ha), Fatasil RF (1966, 669.02 Ha), Amchang RF (1972, 5318 Ha), South Amchang RF (1990, 1550 Ha), Hengrabari RF (1972, 579 Ha), Gotanagar RF (1984, 171 Ha), Sarania RF (1989, 7.99 Ha), South Kalapahar RF (1989, 70 Ha), and Jalukbari RF (1990, 97.70 Ha). (Jacob 1938, Das 1973, Swargowari 2002). The first figure in the brackets is the year of notification of the RF, while the second figure is area of the RF in Hectares. The forests on the southern periphery of the city have Sal formations mixed with patches of Evergreen and bamboo formations. The forests in the city show Moist Mixed Deciduous forest formations. Where soil is shallow and poor, stunted growth of bamboo and scrub occur. The working plan records over the years show that the density of the forests have progressively declined. To quote M. C. Jacob (1940), “Existing Unclassed State Forests are being jhumed extensively, have been and being rapidly taken up for cultivation by immigrants from Bengal as well as the indigenous people and are deteriorating rapidly under uncontrolled exploitation of forest produce given free to settlement holders and by grazing. It is, therefore, only a question of time before this type of forest is wiped out.” Increase in population is one of the most important parameters leading to forest depletion. The Forests of the city are depicted in **Map No. 5.3**.

5.2.3 Wetlands of Guwahati

The Guwahati city is drained on the north by the Brahmaputra river. The other major rivers and streams are Amchang nadi, Bashsitha nadi (Barpani), Bharalu nadi, Bonda nadi, Bukat nadi, Kalmani nadi, Kana nadi and Mora nadi. There are several other streams and rivulets. The Deepar Beel[75] is the largest water body and a Ramsar site[76]. Part of its also declared as wildlife sanctuary[77]. The other main waterbodies are Borsola beel, Bordal beel, Chunchuki beel, Damal beel, Hachora beel, Khalkhowa beel, Rangagora beel, Silsako beel, Tepal beel, Thengbhanga beel and Thupdhara beel. There are several other water bodies, swamps and mud pools in the city limits. In addition, the largest man made water tank is the Dighali Pukhari. The other major water tanks are Silpukhuri and Jurpukhuri (two ponds together). There are several other artificial water tanks in the city. Some of these names have been variously extracted by the author from the topographic sheets pertaining to Guwahati. The main rivers and wetlands of Guwahati are depicted in **Map No. 5.4**.

5.2.4 Agriculture in Guwahati

Most of the low lying areas in the city limits, in the earlier days, been subject to cropping. As the city grew, the agricultural areas have steadily shrunk (Manta & Rajbanshi, 2015). Agriculture is mostly confined now in the outskirts of the city, especially in areas surrounding the Deepar beel, and North Guwahati. Since most of the areas are low lands, and agriculture is largely rainfed, the cropping system can be described as lowland rainfed floodplain (RFFP) agricultural regime.

5.3 Guwahati City Population and Built Up Growth

Known as Pragjyotishpur in ancient times, Guwahati settlements date back to 4-7th century AD. The city had eight municipal wards in 1874 with an area 6.4 km^2 (Hemani & Das, 2015). With a

75 Beel or Bil in local language means waterbody or lake.
76 Declared Ramsar Site in November, 2012
77 Deepar Beel declared a wildlife sanctuary in 2009 with an area of 4.14 km^2.

modest population of about 8000 inhabitants towards the end of 19th Century, the city holds today more than a million population. The built up of the city grew from 8.59 km^2 in 1911 to 176.19 km^2 in 2015, showing a growth of 21 times **(**Yadav R and Barua A, 2016**)**. Before going into the case study proper, the city growth dynamics is discussed briefly in the paragraphs below.

5.3.1 Guwahati City Population Growth

The Guwahati city population was estimated at 8394 in 1891 (GMDA, 2005). The population of the city at different periods of time is given in **Table No. 5.1** taken from Yadav and Barua, 2016:

Table No. 5.1: Population and Decadenal Growth of Guwahati Cty

Year	Population	Decadenal Growth Rate (%)
1891	8394	
1921	16480	25.22
1961	199482	86.52
1971	293219	46.99
1991	646169	48.45
2001	890773	37.85
2011	968549	8.73

From 1891 till 2011, the city population grew by 115 times. The decadal growth rates are shown in column 3 of the **Table No. 5.1.** Since the map and satellite images used for the city growth study used in built-up and AFOLU studies, pertained to specific years only, the population for the corresponding years was estimated based on the above population data and growth rates. Based on the above growth rates, the following population estimates have been arrived at for the Guwahati city for the study years for further analysis which was taken from Yadav & Barua (2016). Similarly population estimates were arrived at for the years 2005 to 2016 for use in the energy and building studies. These are given in **Table No. 5.2**.

Table No. 5.2: Population of Guwahati City for Selected Years

Year	Population	Year	Population
1911	13785	2009	954919
1967	255724	2010	963255
1986	557932	2011	968549
2003	906394	2012	999349
2005	922288	2013	1031128
2006	930340	2014	1063918
2007	938462	2015	1097751
2008	946655	2016	1132659

5.3.2 Guwahati City Built Up Growth (1911-2015)

Built up area of the Guwahati city stands for the years **1911**: 8.59 km^2, **1967**: 54.48 km^2, **1986**: 90.65 km^2, **2010**: 142.75 km^2 and **2015**: 176.19 km^2 (Yadav & Barua 2016). The growth rate of the built area of the city from the 1911 baseline, along with the year to year growth rate is pictorially presented in the **Chart. No. 5.1**. The chart shows that the city has grown rapidly from 1986 onwards expanding by almost 2 sq km annually. However, this growth has jumped three times from 2010. This growth rate arrived from GIS data shall be examined in more detail in the building case study. The GIS map of the built up and growth of the city from the period 1911 to 2015 is shown in **Map No. 5.5**. It is seen that the built up area grew almost by 21 times from 1911 to 2015. The annual built up growth rates from 1986 to 2010, and from 2010 to 2015 were used to work out annual built-up areas that were used in the electricity consumption and the building sector case study.

5.4 Why Guwahati City?

As is seen from the population growth (Table 5.1) and built up area of Guwahati city (**Map No. 5.5**), Guwahati has been growing at a rapid rate. Further, Guwahati is the capital city of Assam, and is considered the Gateway to the north east India, as well as the south east Asia. It is also the business and commercial hub of the region, and connects the north east India to the rest of the country by rail, road and airways. Guwahati was recognised as a Metropolitan status in 2015 after its population crossed 1 million. It is also one of the selected 100 smart cities by the Ministry of Urban Development, Government of India, which is a new initiative to drive economic growth and improve quality of life of people by enabling local development. This program falls under the Smart City Mission of the Ministry. In its present urbanized form, Guwahati is the biggest city of the North East India. This makes a good case for studying urbanization from a sustainable development perspective by linking it with improved standard of living as well as higher levels of emissions. With the rise in population, the built-up growth was triggered impacting upon the ecosystems of the city negatively. At the same time, the consumption of energy has also increased manifold. Guwahati, being the biggest city of Assam as well as the North-East India, has seen a large spurt in building construction activities such as malls, hospitals, educational institutions, and business and commercial hubs that cater to the whole of the region. Therefore, Guwahati is an interesting case to study its growth in energy consumption, building construction and shrinkage in the natural ecosystems such as forests, wetlands and agriculture farming systems as a fall back of the urbanization process. The energy matter transformation through the city growth engine offers an excellent opportunity to study the emerging patterns in emissions and entropy generation. The city, thus, also offers an opportunity to study the current trends and make future projections in order to explore the pathways for evolving a sustainable city model.

PART B

5.5 Case Study: Methods Used

5.5.1 What is being measured?

The case study entailed measurement of two parameters namely CO_2 emissions and entropy generation in various identified economic activities and processes. Values for CO_2 emissions and entropy were measured for the sectors from available data. All the measurements were categorized in the following types:

1. Direct CO_2 & Entropy
2. Indirect CO_2 & Entropy

The details of the system boundaries defining direct and indirect relationships are discussed subsequently in Section. 5.5.7 and 5.5.8.

5.5.2 Sectors studied

The city is considered as an open system exchanging energy and matter with its surroundings. Working Group III AR5 (IPCC, 2014) categorizes 5 sectors of the economic activity as contributory towards emissions being energy intensive. These sectors include energy, transport, buildings, industry and Agriculture, Forestry and Other land Use (AFOLU). For the present study, the focus has been on energy use for which electricity consumption, fossil fuel consumption in transport and other activities, fuelwood and LPG were considered. In the building sector, the study focused on direct and indirect energy use and carbon emission in building construction. In the AFOLU sector the focus was on carbon emission in forestry (change of land-use to settlements), agricultural cropland (paddy) and wetlands of the city.

5.5.3 Data Sources

Primary and secondary data of the intended sectors of study were obtained from the concerned departments. Primary data was collected from the registers and records of the departments concerned. It consisted mainly of time series data with varying periods for different sectors. Secondary data in form of DPRs, reports, audit reports, research studies etc. were collected. The details of various data sources for each of the sectoral case studies are presented at the end of this chapter. The gathered data was checked for errors, data gaps and inconsistencies in values and units. Detailed description of the various data sources have been provided in the corresponding case study treatment.

5.5.4 Analytical Methods

Standard statistical methods such as mean, standard deviation, standard error, correlation, regression analysis using spread-sheets were applied on the datasets. Standard values and factors for sector specific emission calculations were taken from published reports of the IPCC and other repositories such as World Bank, WRI, ICE, CDIAC, IEA, GEA and other publications and international reports. India specific data and factors were obtained from reports of the Planning Commission of India (now NITI Aayog[78]), and reports of the concerned Ministries & Departments. Data and factors pertaining to Assam and the case study area were obtained directly from the published reports of the Government of Assam such as the Statistical Handbook, Socio-Economic Surveys, Census data etc, and other published reports of the State and the Central Governments.

5.5.5 Sector Specific Methods

Kummel (1989), and Kummel and Schussler (1991) have shown that pollutants such as noxious gases can be easily brought into the fold of entropy by taking their heat equivalents. Once in the

78 NITI Aayog (http://niti.gov.in)

fold of entropy, this could be used as pollution indicator in macroeconomic modelling. The authors argue that once this is a part of the model, parts of capital, labor and energy shall go into abatement of pollution, and to that extent shall not contribute to the growth of the goods and services. The authors define Heat Equivalence of Noxious Substances (HEONS) as the equivalent amount of heat required to eliminate a pollutant to acceptable levels in a production process. The authors use the following principle to estimate energy and waste heat in the physical and chemical processes:-

1. **Rule 1**: Mechanical and electrical energy used to overcome friction, their transformation to potential energy (which does not perform work subsequently) are counted as waste heat. [*This is similar to First Law efficiencies*]

2. **Rule 2**: Fraction of the supplied heat which is not transformed into chemical bonding energy are to be treated as waste heat. The enthalpy of exothermic reactions is also waste heat, *unless the same is absorbed in another endothermic reaction*.

3. **Rule 3**: The additional waste heat generated for pollution control goes to HEONS accounting.

4. **Rule 4**: The energy input used for transportation of goods/materials is to be counted as waste heat, as all is dissipated by friction at some time or the other.

Rule 1 and Rule 2 have been used in the waste heat estimation and entropy calculation in this study. The Rule 2 has two components namely Second Law efficiencies and waste heat of enthalpy of exothermic reactions.

Entropy and GHG Emissions: Pezzango and Rosini (2014) have studied city from entropy perspective using GHG emission inventory. The authors argue that "GHG inventories represent a particular vision of a general thermodynamic problem: the radiative forcing determined by GHG emissions represent a reduction of the capacity of the atmosphere to expel entropy, hence influencing the efficiency of all the underlying processes." The authors also advocate the "Consumption principle" i.e. "accounting of emissions generated outside the system, but related to the internal activities" should be considered along with the "production principle" i.e. "accounting of all emissions related to the activities within the boundary". This has been termed as "mixed approach". This study follows the mixed approach, as both the consumption as well as production principles have been used to estimate CO_2 emissions and entropy generation in the city case study.

CO_2 and Entropy Equivalence: Entropy as per unit temperature energy content is linked to mass of a substance through molar heat capacities (Kennedy et al, 2015). The equations used are mentioned below:-

$$S_{Total} = S_T + S_R + S_V + S_E + S_N \tag{5.1}$$

where S_{Total} is the total entropy of the system, and S_T, S_R, S_V, S_E, S_N are translational, rotational, vibrational, electronic and nuclear spin motion contributions to the entropy of the molecule, and

$$\Delta S = \Delta S^0_{298} + \int_{298}^{T} \frac{C_p}{T} dT \tag{5.2}$$

where ΔS is the entropy of the gas i.e. CO_2 at temperature T, ΔS^0_{298} is the entropy at NTP, C_P is the heat capacity at temperature T. This equation would be useful in estimating entropy of CO_2 at various temperatures at which it is released from the different processes in the system such as exhaust of vehicles, chimney of a thermal power plant or cement kilns. In this study, it has been assumed that CO_2 is released at 298K, and has an associated entropy of 213.66 J $mole^{-1}$. This translates to 4.86 MJK^{-1} of entropy per 1 metric tonne of CO_2. This factor has been used to convert all CO_2 to corresponding entropy values.

5.5.6 Classification of Economic Activities

The economic activities selected for the Case Study were as per the International Standard Industrial Classification of All Economic Activities (ISIC) ver 4. The codes used from ISIC for the study are: 0112:Growing of rice, 0220:Logging, 4100:Construction of buildings, 2394:Manufacture of cement, lime and plaster, 2392:Manufacture of clay building materials, 2410:Manufacture of basic iron and steel, 49:Transport, 1920:*Manufacture of refined petroleum products, 9820:Undifferentiated service-producing activities of private households for own use and 3510:Electric power generation, transmission and distribution.* The details of the ISIC Codes are provided in Appendix-1 for the activities considered in the Case Study. The study sectors wrt direct and indirect entropy generation and CO_2 emission are depicted in the **Fig No. 5.2.**

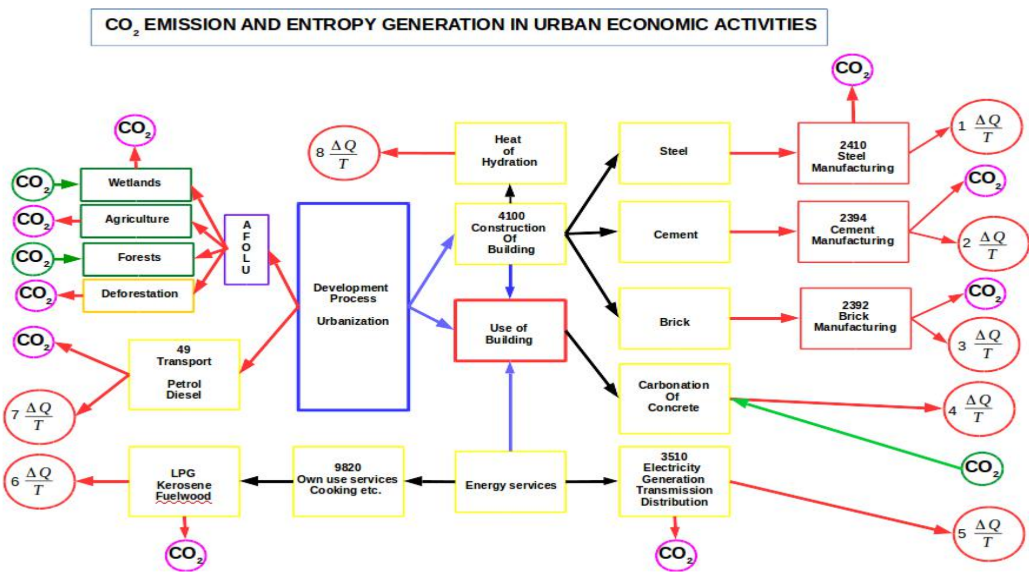

Fig No. 5.2 Entropy & CO_2 Generation Schematic of the City Case Study of Guwahati

5.5.7 Systems Boundary

The GMDA administrative boundary was considered as the system boundary for this case study. However, the forests, hills and wetlands boundaries may not exactly coincide with the GMDA boundary. Nevertheless, areas falling within the GMDA boundary alone for the natural systems have been considered.

5.5.8 Direct and Indirect Emissions from Economic Activities and Processes

CO_2 emission and entropy generation outside the boundary of the city was taken to be “Indirect”, while all emissions and entropy generation within the defined city boundary were considered to be “direct”. The material and energy involved in each of the economic activities were examined, and direct and indirect sources of CO_2 emission and entropy generation were identified. For each of the process the physical and chemical processes were identified. The CO_2 emissions and entropy generation, process wise, for each of the activities were considered individually in the study. For a unit of the energy/mass involved/consumed (directly or indirectly) in the processes of the identified economic activities, values of emission of CO_2 and entropy were worked out as a factor. These values, thereafter, were multiplied with the inventorized/collected aggregate values of the energy/mass in units such as metric tonnes (MT), Million Units (MU), Kilo Litres (KL) and square meters (Sq M) to arrive at the total annual CO_2 emission and entropy generation for the city from the sources considered in the study.

5.5.9 CO_2 Emission Estimation Methodology

CO_2 emissions from all sources can be summed up in the following general equation:

$$CO_{2_{Emissions}} = \sum_{Category} A \bullet \mathrm{EF} \qquad (5.3)$$

Where CO_2 Emissions is the emissions of CO_2 from all its source categories, A is the amount of individual source category utilized which generates emissions, and EF is the emission factor for a given type of source category of energy.

CO_2 Emission using Tier I Methodology: IPCC Tier I methodology/ factors/ values were taken for CO_2 emission calculations arising out of MS, HSD, LPG, Kerosene (KOIL) and Fuelwood as there were no country specific factors or values available. The basic equation used for this purpose is:

$$CO_2 \; Emission = Fuel\ consumption \bullet Net\ Calorific\ Value\ of\ Fuel \bullet Emission\ Factor \qquad (5.4)$$

The above equation would depend upon the units of fuel consumption. IPCC uses Gigagrams (Gg) as unit of fuel consumption, TJ Gg^{-1} as unit of NCV and tCO2 TJ^{-1} as unit of emission factor (IPCC, 2006). In the case study, data collected was in Kilo Litres (KL) for MS, HSD and KOIL, and in Metric Tonnes (MT) for LPG and fuelwood. Appropriate conversion factors were used. The modified equations are given below:

For MS, HSD & Kerosene:

$$F_{CO2}=1\ (KL) \bullet FD\ (KgL^{-1}/1000) \bullet NCV\ (TJ/Gg) \bullet EF\ (tCO_2/TJ) \qquad (5.5)$$

For LPG:

$$F_{CO2}=1\ (MT) \bullet (1/1000) \bullet NCV\ (TJ/Gg) \bullet EF\ (tCO_2/TJ) \qquad (5.6)$$

For Fuelwood:

$$F_{CO2}=1\ (MT) \bullet NCV\ (TJ/MT) \bullet EF\ (tCO_2/TJ) \qquad (5.7)$$

where F_{CO2} is factor of CO_2 emission per unit (1 KL or 1 MT) of fuel consumed, FD is fuel density, NCV is Net Calorifc Value and EF is emission factor as given by IPCC Guidelines. The emission factors and net calorific values were taken from the IPCC 1996 and IPCC 2006, while the Fuel density was taken from IEA (2004). These values are given in the **Table No. 5.3** below:

Table No. 5.3: Emission & Other Factors for Various Fuels

Fuel (1 Unit)	Fuel Density	Net Calorific Value	Emission Factor (tCO_2/TJ)	Remarks (Source)
MS	0.741	44.30 TJ/Gg	69.30	IPCC 2006, IEA 2004
HSD	0.844 Kg/Litre	43.00 TJ/Gg	74.10	IPCC 2006, IEA 2004
LPG	-	47.30 TJ/Gg	63.10	IPCC 2006
Kerosene	0.803 Kg/ Litre	43.80 TJ/Gg	69.30	IPCC 2006, IEA 2004
Fuelwood	-	0.015 TJ/tonne	109.60	IPCC 1996

CO_2 Emission using Tier II Methodology: The Tier II methodology of IPCC is applicable when emission factors are taken from national level studies, rather than default value given by IPCC. The methane emission value for paddy crops was taken from the Methane Asia Campaign 1998 (Jain et al, 2004). The expression used for calculating emissions from the cropping fields of 1 sq km is given below:

$$F_{CO2}=1\ (Sq\ Km) \bullet GWP_{CH4} \bullet EF\ (g\ m^{-2}) \qquad (5.8)$$

As per IPCC (1996, 2006), GWP_{CH4} was taken to be 21, and the value of EF_{CH4} was taken to be 19 g m^{-2} from the Methane Asia Campaign. Similarly the Tier II methodology was applied to assess the carbon loss from logging/ deforestation and conversion of forested areas to settlements. The FSI assessed carbon stocks for Assam was taken as having an average carbon pool of 61.10 tC ha^{-1} (FSI, 2011). For 100 ha (=1 sq km) of forest loss to settlements, the corresponding loss of carbon comes to 6110 tC / sq km which translates to 22403.33 tCO_2 ($E_{tCO2} = E_{tC}*44/12$). Therefore, an emission factor of about 22400 tCO_2 per sq km has been used.

CO_2 Emission using Tier III Methodology: This methodology was used in case of the energy sector study involving electricity consumption and building construction study, where it was not possible to use any factor directly from literature. Existing factor vales from literature were used to build specific sector wise emission factors. These are briefly discussed below:-

In respect of estimation of CO_2 emission (indirect and embodied) for buildings, a combined factor per sq meter of building construction was evolved combining emissions from clinker formation (IPCC, 2006), and using literature review to assess use of fuel and electricity in a typical dry kiln process, CO_2 emissions for steel and brick. Using the local PWD construction norms, the CO_2 emission associated with per sq m of building construction in Guwahati was found to be 0.485 tCO_2 for GF, 0.323 tCO_2 for OF and 0.211 tCO_2 for AT (See **Appendix-3B** for more details)

In case of assessing CO_2 emission from electricity use per unit of consumption at house hold (HH) level, the following methodology was adopted. The flow of energy from the Thermal Power Plant (TPP) to HH was worked out based on the efficiencies and relationships given in Eq No. 5.22 to 5.24. For 1 Unit of electricity supply at HH level, the total energy inputted at the TPP end comes to 2.9173 U (=10.5023 MJ). Assuming 35% efficiency at HH level, it is seen that only 0.35 U is consumed in useful work and enjoyment of life, and rest of the 0.65 U gets converted into waste heat and lost to the surroundings. Total energy wasted in the entire chain (within and without the city boundary) from plant to household comes to 10.109 MJ, giving an efficiency of only 3.75%. In the process, 1.174 Kg of CO_2 is emitted (indirectly) and 0.922 Kg of coal consumed at the thermal plant end for every 1U of energy supplied at the HH level. As regards entropy generation, it is seen that total entropy generation from HH to plant comes to 33.924 kJK^{-1}, of which 9.478 kJK^{-1} entropy is generated directly within the city limits (in HH-DTR system), and 24.446 kJK^{-1} entropy is generated indirectly beyond the city limits (in Grid-Plant system). These are depicted diagrammatically in Fig No. 5.3.

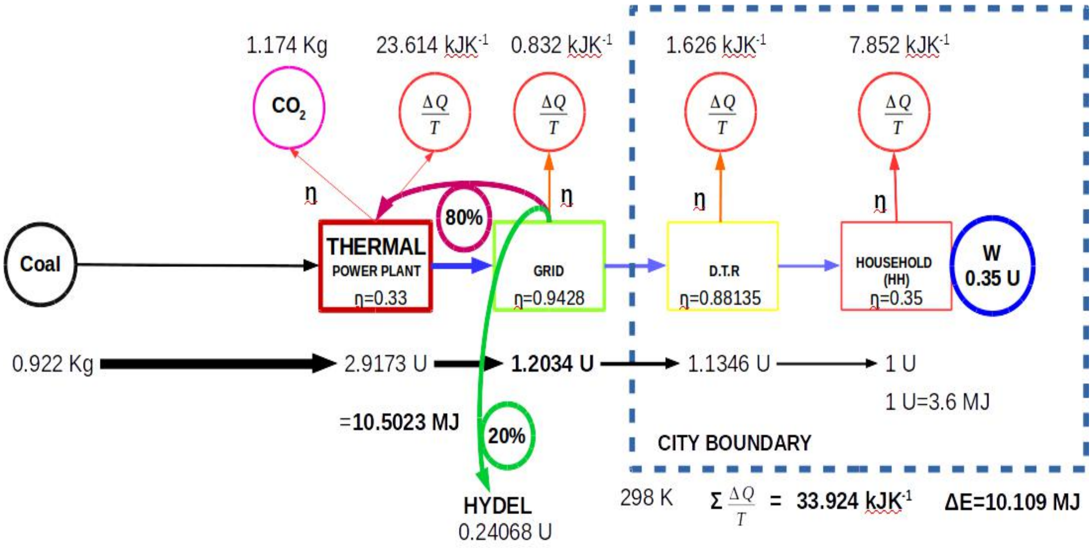

Fig No. 5.3: Entropy Generation (Direct & Indirect) and CO_2 Emission for I Unit Electricity

The formulae and factors used in the above calculation are given in the **Appendix-3A**.

5.5.10 Entropy Estimation Methodology

As a general principle, the following methods were used for entropy calculations:

1. Wherever possible, the firstly efficiency values of the energy conversion interfaces such as appliances etc. were either estimated from published literature, or assumed.

2. The efficiency was calculated from the following relationship:

$$\eta = \frac{E_{Output}}{E_{Input}} \qquad (5.9)$$

3. The entropy was worked out assuming that energy loss happened at 298 K (25^0C):

$$\Delta S = \frac{\Delta E_{Loss}}{298} \qquad (5.10)$$

4. If input energy values were available, then efficiency values were used to estimate energy loss as per the basic equation:

$$\Delta S = \frac{E_{Input} \cdot (1 - \eta)}{T} \quad (5.11)$$

5. If several processes with different efficiencies were involved, multiplicative property of efficiency was used to arrive at the total efficiency as per the basic equation:

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \ldots \cdot \eta_n \quad (5.12)$$

6. In cases where theoretical heat (i.e. heat required to achieve a process as per the exact chemical reactions involved in the process) was known, balance of the heat supplied was treated as heat loss. This can also be termed as the Second Law Efficiency.

$$\Delta E_{LOSS} = E_{INPUT} - E_{THEORETICAL} \quad (5.13)$$

7. Molar entropy value of CO_2 at 298K, as published in standard thermodynamics textbooks, was used to convert tCO_2 into TJK^{-1} of equivalent entropy.

Using First Law Efficiencies: The First Law efficiencies (also known as thermal efficiency) were used to estimate entropy in respect of combustion of fuels MS and HSD (assumed at 40%), LPG (60%), Kerosene (38%) and Fuelwood (9%). In case of electricity consumption, efficiency at household level (HH) was assumed to be 35%, at DTR level at 88%, Grid level at 94% and at plant level 33%. However, it was further assumed that only 80% of all the electricity demand of the city was met from thermal sources, rest being hydel. Energy losses were accordingly worked out as per (E_{INPUT}-E_{OUTPUT}) as given in the preceding paragraphs.

Using Second Law Efficiencies: The Second Law efficiencies were used in estimating heat losses in the cement process (clinker formation), brick making and steel manufacturing processes to arrive at indirect (embodied) entropy associated with cement, steel and brick used in building construction. In each of these processes, the theoretical heat requirement as per chemical reaction was found out from standard textbooks on the subject matter and published papers and reports.

The actual amount of heat supplied to achieve the processes was taken from literature. The difference was assumed to be heat loss and entropy was calculated at 298K accordingly.

Using Enthalpies of Reactions: The enthalpies of reactions, if the process was found to be exothermic in nature, were used to estimate heat lost to the surroundings due to the process. The two specific instance in the present study are the heat of hydration and the heat of carbonation. The heat of hydration is generated during curing of cement in the construction process. Heat of carbonation is the amount of heat released when concrete absorbs CO_2 from the atmosphere. It is the reverse of calcination. Since these are waste heat, the entire enthalpy value for both the processes was used to estimate entropy at 298K. In both the cases, heat is completely lost to the surroundings.

5.5.11 Summary of Factors of Emission

Table No. 5.4: Summary of Emission Factors Used in the Study

Sl. No.	Economic Process (Unit)	Factors for Entropy (TJK^{-1})		Factors for CO_2 Emission (tCO_2)		Remarks
		Direct	Indirect	Direct	Indirect	
1.	MS (1 KL)	66.0732×10^{-6}		2.274863		Tier I
2.	HSD (1 KL)	73.07114×10^{-6}		2.689234		Tier I
3.	LPG (1 Metric Tonne)	57.14094×10^{-6}		2.984630		Tier I
4.	KOIL (1 KL)	73.17540×10^{-6}		2.528824		Tier I
5.	Fuelwood	45.80537×10^{-6}		1.644		Tier I
6.	Electricity (1 MU)	9.478×10^{-3}	$21.536 X 10^{-3}$		1174	Tier III
7.	Forest to Settlement (1 Sq Km)			22400		Tier II
8.	Cropland (1 Sq Km)			399		Tier II
9.	Wetland (1 Sq Km)			18.66		Tier I
10.	Building (1 sq m)	8.57×10^{-6} 5.92×10^{-6} 3.91×10^{-6}	6.83×10^{-6} 4.60×10^{-6} 2.73×10^{-6}		0.485 0.323 0.211	GF* Tier III OF* ,, AT* ,,

PART C

5.6 GUWAHATI CITY CASE STUDY – SECTORAL PRESENTATION

The four sectoral studies namely electricity consumption, fossil fuel consumption, buildings and AFOLU have been dealt with in each of the sections below.

5.6.1 ENERGY SECTOR: Guwahati City Electricity Consumption Case Study

The energy sector consists of direct and indirect energy studies in electricity consumption, fossil fuels and indirect (embodied) energy in buildings. However, the last two fields have been treated as separate sectors and dealt with accordingly. This section dwells only on electricity consumption.

The world electricity consumption reached 19841 TWh in 2014. The average growth rate of electricity consumption in the world since 1974 was 3.4%. In 2014, 66.7% of world electricity production was from fossil fuel generating plants, while hydroelectric sources provided 16.4%, nuclear plants 10.6%, biofuels and waste 2.1%, and geothermal, solar, wind and other sources provided 4.2% (IEA Elec, 2016). The world per capita electricity usage comes to 15000 kWh, that of China is 4000 kWh. India's per capita electricity usage was 914.41 kWh in 2012-13, 957 in 2013-14 and 1010 kWh in 2014-15 (*Live Mint e-Paper, 2015 https://goo.gl/JYBNVb*). The per capita wattage for the world comes to 1712 W, for China the figure is 457 W and for India, it is 115 W. India has 290GW of electricity generation of which 60% is coal, and the rest non-coal sources (IEA India, 2015). The CO_2 emission from hydroelectric plants is one of the lowest compared to other sources such as coal fired plants. Coal fired plant could emit 900-1200 Kg CO_2/MWh, while hydro plants emission rate stood at 0.5-152 Kg CO_2/MWh (Steinhurst et al, 2012)

5.6.1.1 Data Sources

The case of Guwahati city was studied from the available distribution and consumption data in form of energy in Million Units (or GWh or 10^9 Watt Hour) injected at the DTR (Distribution Transformer) level and energy billed in Million Units at the consumer level (called here House Hold or HH level). The Assam Power Distribution Company Ltd (APDCL[79]), which is responsible for buying power from various sources and distributing in the same in the city, has 7 zones and 19 Circles in the Assam, of which GEC I and GEC II cover the Guwahati city. Data on electricity consumption for last 10 years (2005-06 to 2015-16) was collected from the APDCL for the two circles for industrial and non industrial consumers with monthly energy consumption breakup. The data for the state of Assam for energy billed was collected from various published sources (GoA, 2014). Secondary data on electricity consumption for 15 cities of India was also collected from CEA[80] Mega City Survey (CEA, 2013) and website of MoUD[81], Govt. of India.

5.6.1.2 Objectives of Study and Key Questions

The study aims to arrive at direct and indirect emissions and entropy generation associated with electricity consumption of Guwahati city (2005-06 to 2015-16), and then explore certain scenario pathways to see how the emissions can be maintained at the current levels in 2025-26 in view of the projected rise in electricity demand due to rise in population and life style related demands. The key questions that the study seeks to answer are:

1. Is there a relationship between entropy and energy consumption in the urbanization process?
2. Can reduction in entropy generation be used as an indicator of sustainable development?

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79 APDCL is the power utility company of the Government of Assam set up in 2009 (http://www.apdcl.gov.in)
80 CEA- Central Regulatory Authority is the main power regulator of India established since 1973 (http://www.cea.nic.in) under the Electricity Act, 2003
81 http://moud.gov.in

5.6.1.3 Methodology

The general methodology used has already been described in Part B of the Chapter above (Para 5.5.9 and 5.5.10). However, the next three sections deal with the methods deployed for data analysis and projecting certain scenario pathways (5.6.1.4 to 5.1.6.6).

5.6.1.4 Study of Rise in Electricity Consumption of Guwahati City

In order to understand the growth pattern of the city wrt population growth and increase in energy consumption, time series data on annual electricity consumption was collected for a decade. Assuming that electricity consumption (E_{HH}) is a linear function of population (P), built up area (B) and lifestyle (represented by Per Capita Wattage, W), the following relationship is proposed:-

$$E_{HH} = f(P, B, W) \tag{5.14}$$

$$E_{HH} = c_1 \cdot P + c_2 \cdot B + c_3 \cdot W + c_0 \tag{5.15}$$

where c_1, c_2, c_3 and c_0 are constants.

The Per Capita Power (PCP) of the population (P) in Watts (W), is given as:

$$PCP(W) = \frac{E_{HH} \cdot 3.6 \cdot 10^{12}}{P \cdot 10^{6} \cdot 24 \cdot 365.25 \cdot 3.6 \cdot 10^{3}} \tag{5.16}$$

where E_{HH} is in Million Units (MU).

In order to be able to use the Eq 5.14 and 5.15 effectively, it would be necessary to project values of built up area as well as per capita wattage. To achieve this, it was assumed that both built up as well as per capita wattage were functions of population as given below:

$$B = f(P) \tag{5.17}$$

$$W = f(P) \tag{5.18}$$

$$B = c_1 \bullet P + c_0 \tag{5.19}$$

$$W = d_1 \bullet P + d_0 \tag{5.20}$$

5.6.1.5 Estimation of Low Entropy Resource Use and High Entropy Waste Generation

The electricity consumption at household (HH) level would require a backward linkage from household consumption to thermal power plant production using system efficiencies at different stages. In order to arrive at possible estimates of coal, a primary low entropy resource input, and emission of CO_2 and entropy generation in the entire process from thermal power plant, efficiencies of the system at various stages are required. Efficiency at lower level was used to calculate backwards the associated input energy at the higher levels (DTR, Grid and Plant) level using the relationship:

$$E_{INPUT} = \frac{E_{OUTPUT}}{\eta} \quad (5.21)$$

The details of the actual efficiency values used the above calculation from Household to DTR, DTR to Grid and Grid to Plant are given below:

As a thermodynamic model for entropy study, the unit of consumption was taken to be a Household (HH). In case of electricity consumption, efficiency at household level (HH) was assumed to be 35%, at DTR level at 88%, Grid level at 94% (Crisil, 2010) and at plant level 33%. However, it was further assumed that only 80% of all the electricity demand of the city was met from thermal sources, rest being hydel. Assuming the efficiency values as above from secondary sources at DTR, Grid and Plant level, as given above, the energy input at each level was worked out using the relationships given below, where E is the input energy at each level with appropriate subscript indicating the input level:-

$$E_{DTR} = \frac{E_{HH}}{\eta_{DTR}} \quad (5.22)$$

$$E_{Grid} = \frac{E_{DTR}}{\eta_{Grid}} = \frac{E_{HH}}{\eta_{Grid} \bullet \eta_{DTR}} \quad (3.23)$$

$$E_{Plant} = \frac{0.8 \bullet E_{Grid}}{\eta_{Plant}} = \frac{0.8 \bullet E_{HH}}{\eta_{Plant} \bullet \eta_{Grid} \bullet \eta_{DTR}} \quad (5.24)$$

The last equation assumes that 80% of the grid supplies for the city come from coal based thermal power plant (TPP) sources.

5.6.1.6 What If Analysis of Power Consumption

Two variables, namely efficiency (of the electricity generation, distribution and consumption network), denoted by symbol **η**, and per capita power denoted by **W**[82], were used to carry out a what if scenario analysis of future energy consumption pathways of Guwahati city. The two variables would result in 4 pathways namely:

1. Pathway SC11:Business As Usual (BAU), no change in W or η
2. Pathway SC12:No change in W, per capita power, but increased efficiencies
3. Pathway SC21:Reduced W, per capita power, but no change in efficiencies
4. Pathway SC22:Reduce W per capita power and increased efficiencies

The consumption of primary resource (coal), corresponding CO_2 emission and entropy generation were then worked out for each of the pathways as per relationship given in the Appendix. Wattage reduction was taken in steps of 10W, 30W and 50W. Thereafter, % substitution of the thermal power with renewable energy (green power) was considered in steps of 10% (means 70% Thermal Power), 20% (means 60% Thermal Power) and 30% (means 50% Thermal Power) substitution. The four pathways were overlaid with substitution of thermal power by green power accordingly, and another pathway, namely only green substitution without any improvements W or η was also additionally considered, giving 5 pathways in total. A schematic of the methodology is given in Fig No. 5.4. The various numerical assumptions for the above scenario projections are tabulated in the Appendix-3A (see para B & C).

82 W is different from kWh. The former denotes power at any instant while the latter denotes energy consumed

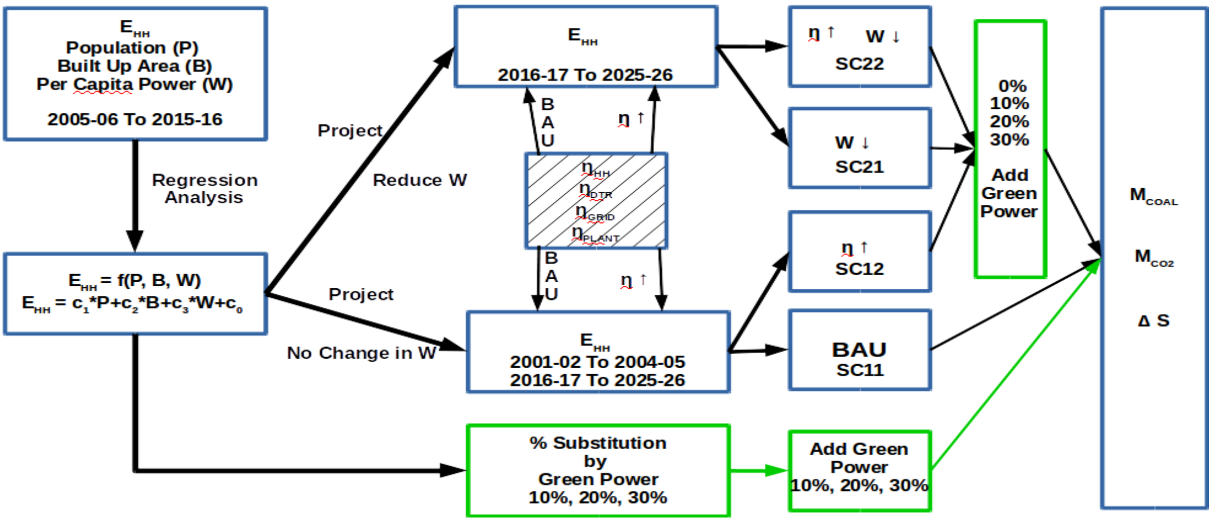

Fig No. 5.4 Flow Diagram of Electricity Scenario Pathways

However, there could be high level of associated costs with increase of efficiencies, reduction in per capita power consumption, and substitution by green power. Working these out is beyond the scope of the paper.

5.6.1.7 Results & Analysis

The electricity consumption of Guwahati city from 2005-06 to 2015-16 is depicted in **Chart No. 5.2A**. The chart shows that the non industrial consumption is very high in Guwahati compared to industrial. While the non industrial (residential and commercial) demand is steadily rising, the industrial demand is slowly decreasing. Possible reason could be dependence of industrial units on solar power. The variation in monthly consumption is depicted in **Chart No. 5.2B**. The chart shows that the electricity demand peaks in the months of August/ September when the summer is at its peak. Based on the electrical energy consumption data of the city, multivariate regression analysis was carried out using free online statistical tools taking population data (see Table 5.2) and built up data as explained in Para 5.3.2, and wattage as explained under Para 5.6.1.4.

The Equation 5.15 emerged as on regression analysis as:

$$E_{HH} = 1082.986715 \bullet P + 0.2957137967 \bullet B + 7.70793366 \bullet W - 1017.59721 \quad (5.25)$$

with coefficient of determination (R^2) value of 0.9999299782, where E_{HH} is in Million Units (MU) and P is in Millions of population, B is built up area of the city in sq km, and per capita wattage in W. Similarly, on regression analysis, the Eq No. 5.19 and 5.20 emerged as:

$$B = 207.0055288917 \cdot P - 50.8444654088 \qquad [R^2=0.9996572142] \qquad (5.26)$$

$$W = 981.7317123249 \cdot P - 851.4697015955 \qquad [R^2=0.9971277041] \qquad (5.27)$$

Based on the Eq No. 5.25, 5.26, 5.27, household electricity consumption (E_{HH}) for Guwahati city was projected upto 2025-26. The E_{HH} values for the period 2001-02 to 2004-05 were also calculated from the equations above.

5.6.1.8 What If Scenario Projection (2001-2025)

Thereafter a scenario projection was carried out using the five alternate future pathways as described in the methodology section (Para 5.3.1.6). The outcome of the scenario analysis is depicted in Table No. 5.5. It depicts percent reduction in resource use and emissions wrt BAU (as % reduction in CO_2 emissions, entropy generation and reduction in resource use (coal) for 2025 for 10W, 30W, 50W and 100W reduction in per capita wattage and 10%, 20% & 30% substitution by green power:-

Table No. 5.5: Emissions Scenario Pathways Summary

Pathways	Scenario SC12			Scenario SC21			Scenario SC22		
	CO_2	Coal	Entropy	CO_2	Coal	Entropy	CO_2	Coal	Entropy
Reduction in Per Capita Wattage (W)									
10 W	18.56	18.60	21.61	3.81	3.81	3.81	21.66	21.70	24.60
30 W	18.56	18.60	21.61	11.43	11.43	11.43	27.87	27.90	30.57
50 W	18.56	18.60	21.61	19.05	19.05	19.05	34.07	34.11	36.55
% Green Substitution									
10	28.75	28.75	28.17	15.83	15.83	12.18	31.47	31.47	30.91
20	38.93	38.93	34.73	27.86	27.86	20.55	41.26	41.26	37.21
30	49.11	49.11	41.28	39.88	39.88	28.91	51.05	51.05	43.52

The Table No. 5.5 has been diagrammatically represented in Chart No. 5.3A, 5.3B and 5.3C for 10W, 30W & 50W reduction scenarios. It can be seen from Chart 5.3B that 30W reduction in power is as good as investing in efficiency of the whole system right at the beginning of the scenario year, while Chart 5.3C shows that 50W reduction is good enough a measure till 2025-26 compared to efficiency enhancement. Together between the given values of W reduction (10W, 30W, 50W) or green substitution (0%, 10%, 20%, 30%), there are in total 12 possible scenario pathways. While Charts 5.3A to C represent the pathways with no substitution of green energy. Four other scenario pathways showing additionally green power substitution have been depicted graphically depicting % green power substitution and W reduction [(10W, 10%), (30W, 10%), (30W, 30%) & (50W, 20%)] at Chart No. 5.4A, 5.4B, 5.4 C & 5.4D respectively. All the charts depict CO_2 emission. Percent reduction in resource use and emissions for the green power substitution pathway (without impacting values of W or η) wrt BAU is given in the Table No. 5.6.

Table No. 5.6 Green Power Substitution Pathways

BAU	% Reduction in CO_2	% Reduction in Coal	% Reduction in Entropy
10% Green Substitution	12.50	12.50	8.70
20% Green Substitution	25.00	25.00	17.40
30% Green Substitution	37.50	37.50	26.10

In order to arrive at the research objective of finding pathways of keeping the emission at the current levels, taking the value of BAU CO_2 emissions of 2015-16 as base, the corresponding level of emission (in %) in 2025 wrt the base value was calculated for each of the scenario pathways, and the same is given in Table No. 5.7.

Table No. 5.7: 2025-26 Emission Projections

Reduction in Per Capita Wattage	0% Green Substitution	10% Green Substitution	20% Green Substitution	30% Green Substitution
BAU (0W)	*SC11:180.15*	*SC11:157.63*	*SC11:135.11*	*SC11:112.59*
10W	SC12: 146.68 SC21: 173.28 SC22: 141.10	SC12: 128.35 SC21: 151.62 SC22: 123.46	SC12: 110.01 SC21: 129.96 SC22: 105.82	SC12: 91.68 SC21: 108.30 SC22: 88.18
30W	SC12: 146.68 SC21: 173.28 SC22: 141.10	SC12: 128.35 SC21: 139.61 SC22: 113.68	SC12: 110.01 SC21: 119.67 SC22: 97.44	SC12: 91.68 SC21: 99.72 SC22: 81.20
50W	SC12: 146.68 SC21: 173.28 SC22: 141.10	SC12: 128.35 SC21: 127.68 SC22: 103.89	SC12: 110.01 SC21: 109.37 SC22: 89.05	SC12: 91.68 SC21: 91.14 SC22: 74.21

5.6.1.9 Key Findings, Analysis and Discussion

The key findings of the study are summarized in the Table No. 5.8.

Table No. 5.8: Key Parameters of Electricity Consumption (2001-02 to 2025-26)

	2001-02 (Back Calculated)	2005-06 (Estimated Actual)	2015-16 (Estimated Actual)	2025-26 (Projected BAU)
Electricity Consumption (MU)	156.68	441.62	1122.83	2022.77
Per Capita Power (W)	23.03	54.62	116.68	173.54
CO_2 Emission (Mt)	0.184	0.518	1.318	2.375
Coal Use (Mt)	0.144	0.407	1.035	1.865
Entropy Generation (TJK^{-1})	5.135	14.982	38.091	68.62

The study further indicates that:

1. Guwahati touched 1.12 TWh of electricity consumption in 2015-16, from 0.157 TWh in 2001-02. The consumption is likely to double to 2.20 TWh in 2025-26.
2. The average per capita annual power consumption Guwahati city was 176 kWh in 2001-

02 and it stood at 1023 kWh in 2015-16. This is projected to become 1347 kWh in 2025-26. The all India average was 1010 kWh in 2014-15.

3. The per capita power (in Watts) doubled from 23 W in 2001-02 to 55 W in 2005–2006. It again more than doubled to 117 W in 2015–16. The per capita power consumption is estimated to reach to 174 W in 2025-26.
4. It is seen that entropy generation is reduced only by 8.7% per 10% green power substitution, while emission and resource use are reduced by a larger percentage of 12.50.
5. About 35% substitution by green power in the grid can keep the emissions levels to that of 2015-16, without reductions in W or efficiency enhancements.
6. Entropy reductions are not so much impacted by green power (other than TPP side eliminations in entropy generation) as by increased efficiencies, as can be seen from Chart No. 5.5A. By greening of the energy, only thermal power plant side entropy can be eliminated, and rest of the entropies do not get impacted at all. Efficiency enhancement (See Chart 5.5A - SC12 Entropy Line) is the best way to reduce entropy production, while reduction in Wattage (W) (See Chart 5.5A – SC21 Entropy Line) has the least impact on entropy reduction.
7. There is a direct relationship between per capita power usage and CO_2 emissions, as shown in Chart No. 5.5B. Reduction in per capita wattage by 1W leads to reduction in emissions etc. by 0.381% in Guwahati city.
8. Biggest impacts are achieved by a combination of efficiency improvements, per capita wattage reductions and substitution by green power. The best pathway to limit future emissions to the levels of today (and keep it at about 75% of what it is today) is to reduce per capita wattage by 50W, carry out 30% further substitution by green power and increase efficiencies in the generation, transmission, distribution and consumption.

However, the optimal path to keep future emissions at slightly lower levels than today is to pursue a path of 30W power reduction, and 30% further green power substitution. [*No attempt was made to work out the cost implications of the various scenario pathway implementations*].

Further discussion on three topics namely electricity consumption of Guwahati and that of Assam, causes of the growth in consumption whether due to population alone or life styles or both, and how does Guwahati compare with other cities of India in electricity consumption follow in the paragraphs below:

Energy Consumption Patterns, Guwahati vs Assam (2001-2014): The outcome of the study of Guwahati city energy use was compared with that of the State of Assam especially in respect of total energy consumption, population growth, per capita power demand from 2001-02 to 2014-15. Guwahati on average houses 3.22% of the total population of the State (2001- 2014). The population growth for Guwahati as well as the State was about 19% during the period. The energy consumption grew by 117% for the State of Assam during the period, and that for Guwahati grew by 585%. Guwahati had 5% of the total share of power of the State in 2001-02 which grew to 15% in 2014-15. Most spectacularly, the per capita power for Guwahati was 23W in 2001-02, while that of the State was only 14W. In 2014-15, the per capita power for Guwahati rose to 115W against that of State at just 26W. The per capita power of Guwahati grew at 400% from 2001-02 to 2014-15, while that for the State just crawled at 81%. In short*, 3% of the State's most urbanized population uses 15% of the total energy, and individually enjoys 4.4 times the power of it*.

Growth in Energy Consumption- due to population growth or life styles?: Guwahati has seen growth at the rate of 616.65% during the period 2001-02 to 2015-16. An attempt was made to understand how much of this growth could be attributed to normal growth due to rise in population, increase in built up area and to changing life styles demanding higher energy consumption. In order to do so, the per capita wattage factor of 2001-02 was taken as the base lifestyle wattage. Similarly, energy per sq km for 2001-02 was taken as base energy required for built up. The corresponding yearly consumption for the projected populations was taken as the increase in consumption due to population growth. Similarly, an associated increase in power demand due to increase in built up area was also taken into account. The rest of the energy consumption was assumed to be attributed to increased power demand arising out of changing life styles. The Chart No. 5.6 depicts the growth trends of power consumption from population growth, built up area increase and life style demand points of view for Guwahati city. It can be seen from the chart that population related growth in consumption is lower than that of built-up related (more buildings, more power!), and both get over shadowed by life style related consumption which could indicate more number of electrical gadgets, appliances and air conditioners being put to use.

How Does Guwahati Compare with Other Cities of India in energy consumption?: For comparing Guwahati city at all India level and other cities, electrical energy consumption of 15 cities was taken for 2011-12. The all India electrical energy consumption during 2011-12 was 772.603 PWh, per capita consumption being 638.06 kWh, per capita power being in 73W. Guwahati ranked 12th in per capita power with a value of 95W, while it ranked the lowest in total electrical energy consumption of the 15 cities compared. Delhi topped the list with 189 W followed by Surat (182 W), Chennai (172 W) and Hyderabad (165 W). Mumbai ranks 10th with 121 W followed by Kolkata (110 W). This is shown in Chart No. 5.7.

5.6.1.10 Conclusion

The study reveals that the development process is dependent on energy use. Taking electricity as a use case, the study finds that electricity demand increases, in the city context, due to rise in population as well as rise in the city built up area, and life styles. However, the actual growth in electricity consumption depends upon the changing lifestyles which are becoming more and more energy intensive. The study also finds that increase in the efficiencies of electricity generation, transmission, distribution and consumption has a larger impact on reducing carbon emissions and entropy generation than if per capita wattage were reduced. However, in the context of Guwahati city, it is seen that a per capita reduction of 30W-50W in electricity consumption has the same impact as increasing the efficiencies of electricity generation, transmission and distribution system. Further, if 30% more electricity input is obtained from green sources such as hydel and solar power, and a 30W reduction in power is pursued, the city can maintain future emissions at slightly lower than current levels.

5.6.1.11 Limitations of the Study

The limitations of the study are:

1. The HH level efficiency is assumed to be 35%. However, in reality it varies widely from appliance to appliance and depending on actual type of number and appliances deployed in households
2. The coal usage would largely depend upon the quality of coal used in the power plants, and hence its CO_2 emission factor would differ
3. The 20% energy coming from hydel has not been taken into account.
4. The propensity for the consumers to use more efficient appliances could not be measured.
5. Income wise energy usage was not studied. This was mainly due to difficulty in arriving at annual income estimates

5.6.2 Fossil Fuel Use in Guwahati City

Transport sector is one of the key enablers of the world economy with large social connect driving movement of goods and services to various places across the globe. The transport modes include road, rail, air travel, shipping and inland water transport. Transport accounted for nearly 23% of the global energy related CO_2 emissions in 2010. CO_2 emissions from this sector have more than doubled since 1970 to reach 7.0 Gt CO_2 eq by 2010. About 80% of the increase in emissions is due to increase in vehicular road traffic (IPCC AR5, 2014). In the Indian context, the automobile population in India has increased from a mere 0.3 million in 1951 to more than 141 million in 2013. The vehicle kilometer Traveled (VKT) in India was estimated at 1437 billion in 2013 which is estimated to touch 4733 billion in 2030 (CRRI, 2014).

Growth in vehicle registration in Guwahati city from 2007 to 2016, it is seen that overall the growth in vehicle registration was about 176% from 2007 to 2016, indicating an annual growth of about 20%. However, the growth from 2013 to 2016 has been 9%, the period being almost a plateau. Further, it is seen that the petrol vehicles outnumber diesel vehicles by almost six times. Guwahati registers more than 57000 petrol vehicles and about 9000 diesel vehicles annually. Two wheelers (Motorcycles and Scooters) would constitute about 60% of the petrol vehicles. Chart No. 5.8A and 5.8B may be seen in this regard.

With this backdrop, the Case Study on fossil fuels was an attempt to assess the consumption of fossil fuels namely Petrol and Diesel (mostly consumed in transport and power sector). Along with these, LPG and Kerosene were added, though these are mostly consumed in domestic sector only, to give a complete picture of the fossils fuels. While counter sales of petrol and diesel from the petrol pumps of the city determine the amount of fuel consumed annually by the transport and power sector, the LPG and Kerosene sales indicate the amount of fossil fuels burnt in the domestic services.

5.6.2.1 Key Questions

1. What are the direct CO_2 emissions and entropy generation due to fossil fuel consumption in the city?

2. What are the trends in fossil fuel consumption in the City?

5.6.2.2 Methodology

The methodology adopted is explained in detail in section 5.6.5.

5.6.2.3 Data Sources

The annual registration of vehicles was obtained from the website of the Ministry of Road Transport & Highways, Govt. of India. The fuel sales data of petrol and diesel from the petrol pumps (Fuel Station/ Gas Station) of Guwahati city from the year 2010-11 to 2015-16 through M/S Indian Oil Corporation Ltd (IOCL). On request of the Food & Civil Supplies Department, Govt. of Assam. The data on LPG consumption in Guwahati city was also obtained from M/S IOCL. The data on kerosene was obtained from the portal of the Food & Civil Supplies Department, Govt. of Assam. The fuel prices were obtained from the Petroleum Planning & Analysis Cell, Ministry of Petroleum & Natural Gas, New Delhi (https://goo.gl/SjvWsB)

5.6.2.4 Key Findings, Analysis and Discussion

The key findings are enumerated below:-

1. The annual intake of petrol (Motor Spirit – MS), Diesel and LPG are shown in Chart No. 5.9A, and that of kerosene are shown in Chart No. 5.9B. The data clearly shows that that the consumption of diesel was having a rising trend from 2010-11 to 2012-13; while it took a decreasing trend thereafter. The analysis showed that while the MS demand increased continuously, it was not so in case of HSD. It was revealed by the officials on

enquiry that due to improved power supply over the years, diesel consumption has got reduced. Another reason for the reduction in demand for HSD was preference for petrol cars as compared to diesel cars, and rise in the prices of HSD. The trend in the prices of petrol and diesel from 2002 to 2016 can be seen Chart No. 5.9C.

2. In respect of LPG, the consumption trend has been observed to be increasing in nature. This obvious as LPG is the fuel of preference and is being promoted by the Govt. The rise in consumption of LPG can be easily attributed to promotion of LPG as a clean fuel for cooking as compared to firewood and kerosene, which is likely to pick up further under the PM Ujwala Yojana.

3. In respect of Kerosene, there is no clear trend. The consumption is subject to a strong regulatory regime, and allotment depends upon assigned quota to a district.

4. The total annual CO_2 emission from fossil fuels is of the order of 0.864 Mt CO_2 per annum on an average. The per capita CO_2 emission has been steadily declining, and stands at 0.77 tCO_2 in 2015, while it was 0.88 in 2010.

5. The average entropy generation from fossil fuel usage is of the order of 23 TJK^{-1} per annum on an average. The per capita entropy generation has been steadily declining, and stands at 20 TJK^{-1} in 2015, while it was 24 in 2010.

6. On an average, the fossil fuels consumed annually in the city amount to 12 PJ, and the associated CO_2 emissions amount to 0.86 $MtCO_2$, while entropy generated is 22 TJK^{-1}. This is fairly constant, as petrol and LPG consumption is rising while Kerosene and Diesel consumption is declining.

5.6.2.5 Conclusion

In the study period of 2010 to 215, it is seen that the overall consumption of fossil fuels in the city is stable at around 12 PJ, the reason being increasing consumption of petrol and LPG and reduction in consumption of Diesel and Kerosene. Nevertheless, Guwahati is a growing city, and the demand for petrol and LPG would continue to rise, while demand for Diesel and Kerosene would not fall below a certain minimum requirement. The present study is not in a position to throw a light on the minimum requirements of the fossil fuels, as the entire study is based on sales of fossil fuels across various channels, rather than being a consumption based study.

5.6.2.6 Limitations of the Study

The limitations of the study are enumerated below:-

1. The study was primarily based on sales data of fossil fuels.
2. No analysis on vehicle kilometers or passenger kilometers basis was carried out.
3. The study also did not take into account various vehicle types and their efficiency and fuel consumption patterns.
4. The study did not conduct any kind of sampling to estimate number of trips made by people to work, leisure or market.
5. Direct and Indirect usage of energy and associated CO_2 emissions and entropy generation by way of manufacturing/refining/production of the fossil fuels and their transportation to the sales outlets was not studied.
6. Direct and Indirect usage of energy and associated CO_2 emissions and entropy generation by way of manufacturing, transportation and subsequent maintenance activities for the various types of motor vehicles was not considered.

5.6.3 Guwahati City Building Sector Case Study

The literature review revealed that most studies in the building in urban context have been carried out wrt to operation energy use in buildings. There are also studies incorporating embodied energy of buildings. This study focuses on projections of annual addition of floor areas built in the city and their associated carbon footprint and entropy generation. The UNFPA (1996) State of World Population Report prophetically stated that "The growth of cities will be the single largest influence on development in the 21st century." This statement made about two decades ago, was echoed in the UNFPA (2007) State of World Population Report, which said "This statement is proving more accurate by the day. Until now humankind has lived and worked primarily in rural areas. But the world is about to leave its rural past behind..." The Report significantly observes that "The battle for a sustainable environmental future is being waged primarily in the world's cities. Right now, cities draw together many of Earth's major environmental problems: population growth, pollution, resource degradation and waste generation. Paradoxically, cities also hold our best chance for a sustainable future. Urban localities actually offer better chances for long-term sustainability, starting with the fact that they concentrate half the Earth's population on less than 3 per cent of its land area."

5.6.3.1 Key Questions

1. What are the direct and indirect CO_2 emissions and entropy generation due to building activity in the city?
2. What are the material flow and investment in the building sector and how they correlate with entropy generation?

5.6.3.2 Data Sources

In order to account for CO_2 emissions and entropy generation from the buildings, the following building materials have been considered. 1. Cement, 2. Reinforcement Steel and 3. Brick. As regards the emissions and entropy generation from sand and aggregate, the same was not considered. For each of the above mentioned materials, CO_2 emissions and entropy generation have been considered in the following few paragraphs. It is to be noted here that cement and concrete technology in itself is a vast field, and so is steel manufacturing. However, some of the basic and elementary concepts which are essential to arrive at the understanding of the subject matter relevant to the topic has been dealt with. Details of the calculations have been provided in **Appendix-3B**. Building permission primary data was collected from GMDA and GMC. Data and information on embodied energy, CO_2 emissions, chemical reactions, hydration and curing processes was collected through available literature, published reports. Details of data collection, analysis and manner of arriving at emission factors have been furnished in Appendix-2.

5.6.3.3 Methodology

Data analysis and charting was carried out using spreadsheet application. The following are the basic steps used in further data analysis.

1. Data was classified year wise and floor wise year wise floor area was computed. For GMC data only total floor area was worked out year wise.
2. As per PWD data, building construction could be classified in three ways namely:
    i. RCC Ground Floor (GF)
    ii. RCC Other Floors (Higher) 1st floor onwards (OF)
    iii. Assam Type construction (AT)

    Since, the data pertaining to Assam Type construction was very small, it was ignored, and treated, instead, as Ground Floor RCC.

3. Three most important building materials were taken for study namely *1. Cement, 2. Brick and 3. Steel Reinforcement Bar*. The embedded energies, entropy generation and CO_2 emissions for each of these materials were worked out in detail using available published literature, IPCC publications and following Tier 1 and Tier 2 methodologies prescribed by IPCC. All figures were finally converted into per m^2 values as the material consumption data was made available by PWD authorities in per m^2 format. (Details provided in Appendix-2).
4. Based on the per m^2 values of entropy generation, CO_2 emission and energy use, floor wise year wise values of the parameters were calculated. Average construction cost per m^2 as informed by the PWD was used to estimate the likely investments in the construction from 2008 to 2013. The total quantities of materials namely 1. cement, 2. sand, 3. aggregate, 4. Steel Bar and 5. Brick was worked out, and the total projected investment was calculated based on current market prices of the materials.
5. Since Building Permission is a highly regulated activity subject to availability of suitable land use, land use change policy, master plan regulations for the city, it was not possible to arrive at a meaningful trend directly from the primary data. Therefore, a linear regression analysis was carried out between Built Up Area (in Sq Km) and Cumulative Floor Area from 2008 to 2015 as given below:

$$BA = f(FA_{cum}) \Rightarrow BA = c_0 + c_1 \bullet FA_{Cum} \tag{5.28}$$

where BA is built up area in sq km, and FA_{Cum} is cumulative floor area (also expressed in sq km: 1sq km=1000000 sq m)
6. From the Eq No. 5.28, increase in city built up area due to floor area increment was worked out, and thereafter, possible total city floor area estimation was arrived at by dividing the city built up area by the slope of the regression line.

7. Thus, estimation of annual emissions of CO_2 and entropy generation were arrived at taking help of the per sq m factors developed already.

5.6.3.4 Key Findings, Analysis and Discussion

Average Emission Factors Per SQ M: Average of the emission values from 2007 to 2015 was worked for CO_2, direct and indirect energy, direct and indirect entropy generation, which was then divided by the average floor area in m^2 to get the per m^2 values. These values are given in Table No. 5.9.

Table No. 5.9: Emission Values Per M^2 of Construction

CO_2 Emission	409 Kg m^{-2}
Direct Energy	2159 MJ m^{-2}
Indirect Energy	2658 MJ m^{-2}
Total Energy	4817 MJ m^{-2}
Direct Entropy	7.2 MJ K^{-1} m^{-2}
Indirect Entropy	5.7 MJ K^{-1} m^{-2}
Total Entropy	13 MJ K^{-1} m^{-2}

Average Emission Factors Per Capita: The emission factors were divided by the population for the corresponding year and averaged over from 2007 to 2015. Thus, the results obtained are given in Table No. 5.10.

Table No. 5.10: Per Capita Embodied Emissions from Buildings

CO_2 Emission	583 Kg per capita
Total Energy	5506 MJ per capita
Total Entropy	18.29 MJ K^{-1} per capita

Investment in Construction Sector and Emission Footprint of Rupee: The cost of materials, as provided by the PWD is given in Table No. 5.11

Table No. 5.11: Building Materials Cost

Cement	Rs. 6 per kg
Steel bar	Rs. 50 per kg
Sand and Aggregates	Rs. 700 per Cu. M.
Brick	Rs. 8 per piece

Based on the above costs, the total investment in major construction materials (Cement, Steel, Sand, Aggregate & Brick) was worked per annum out from 2007 to 2015 works out to Rs. 693.22 cr. Per m^2 cost of materials on an average for an RCC construction in Assam worked out to be 4814 per m^2.

Built Up Area and Floor Area Relationship: The regression analysis resulted in the following equation:

$$BA = 121.4087 + 3.6285 \bullet FA_{cum} \tag{5.29}$$

The Eq No. 5.29 shows that for Guwahati city, a floor area built up of 1 million sq m (=1 sq km) would typically lead to increase in the city built up area by 3.6 sq km. The Guwahati total built up area for 2015 standing at 176.19 sq km would amount to about total floor area of 49 million sq m. (however, verification of this result was beyond the scope of the present study). Going by the average of 2008 and 2015, annually 1440000 sq m of floor area is estimated to be built up annually, adding about 5.2 sq km built up area. For the period 2010 to 2015, the annual floor area addition comes to 1857777 sq m which translates to a growth of 6.7 sq km per annum in built up area.

The floor wise year wise GMDA building permissions granted is depicted in Chart No. 5.10A The combined floor area data of GMDA and GMC along with cumulative growth in building sector is shown in Chart No. 5.10B & 5.10C. Floor wise data analysis shows that there was a boom in high rise building permissions in Guwahati from 2008 to 2012, after which high rise permission have been almost stopped. The floor wise composition of the city is shown in Chart. No. 5.10D. The mean floor height is G+2. As can be seen from Chart No. 5.1 (Built Up Area Growth Rate Chart), the city has been growing at a rate of about 2 sq km per annum from 1986 to 2010, and the growth got accelerated to about 6.7 sq km per year from 2010 to 2015. The per annum floor area growth rate for the period 2010 to 2015 comes to 1.86 sq km (or 1857778 sq m). It can be safely assumed that Guwahati is adding about 1.86 million sq m of floor area annually. This being the case, Guwahati would be adding about 18.6 million sq m of floor area in next 10 years, amounting to add up of another 67 sq km of built up space. In terms of investment (see Chart No. 5.10E), it amounts to an average annual investment of Rs. 900 cr and about Rs. 9000 cr in the next 10 years (*Actually the investments would be more than double, as the cost in this study is only based on cement, steel, sand, aggregate and bricks*). As can be seen from the Built Up map of Guwahati city at Map No. 5.5, the city would have to grow vertically in next 10 years throwing up challenges of drainage, water supply, sewerage and surface transport.

5.6.3.5 Conclusion

It is seen that building sector, by virtue of use of high carbon footprint input materials such as cement, steel and bricks, is a very big contributor to CO_2 emissions, most of which are indirect and beyond the boundaries of the city. The buildings also have substantial release of heat as heat of hydration at the time of construction and subsequently as heat of carbonation. These contribute to entropy generation directly. The city is seemingly adding 1.86 million sq m floor space annually. The associated carbon emission comes to 0.76 Mt (Million tons) per annum. The entropy generation comes to 24.18 TJK^{-1} annually.

5.6.3.6 Limitations of the Study

The limitations of the study are briefly mentioned below:

1. The study is based on the building permissions issued by GMDA / GMC authorities. The actual construction of the building was not verified on the ground.
2. About 3900 entries of GMDA for 2014 and 2015 were not found usable, as the data was incomplete.
3. No direct sampling of actual material use was carried out on site.
4. This study considers only cement, sand, aggregate, brick and steel. Other building materials were not included in the study.
5. The CO_2 emission and entropy generation was worked out only for cement, brick and steel.
6. Energies of reactions of materials only have been used to arrive at direct indirect entropy generation and CO_2 emission. Energy used in other forms such as in transportation, human labour, onsite generators, lighting etc. was not considered.

5.6.4 GUWAHATI CITY AFOLU CASE STUDY[83]

According to Biello David (2009), Agriculture is responsible for one third of global greenhouse gas emissions from human activity caused by deforestation, nitrous oxide emissions from fields, methane from cattle and rice paddies. The quantum of contribution of these emissions is so high that, quoting the ecologist Jonathan Foley, Director of the Institute on the Environment (IonE) at the University of Minnesota, Biello mentions that the emissions from transporting food, also known as food miles, get relegated to decimal places as rounding errors. Agriculture, forestry and other land use (AFOLU) represents 20-24% of the global GHG emissions, the largest

83 Accepted for publication as Rachna Yadav & Anamika Barua, 2017, Contribution of Urbanization to Emissions: Case of Guwahati City, India, in *Urban Ecology, Water Quality and Climate Change*, Ed. Arup K. Sarma, Vijay P. Singh, Rajib K Bhattacharjya, Suresh A. Kartha, Water Science and Technology Library, Springer, 2017

emitting sector next to energy (Smith et al 2014). The AFOLU sector is particularly important in Asia, which accounts for the largest proportion of global AFOLU emissions. India is the world's fourth largest economy and fifth largest global GHG emitter. In 2000, India's net AFOLU emissions were 146.7 million tCO_2e, accounting for about 11% of the total net national emissions. The agricultural emissions were 355.6 million tCO2e, accounting for 23% of gross national emissions and 96% of gross AFOLU emissions in the same year (AFOLU Working Group 2016). Although AFOLU is not the largest emitting sector in India, Forestry and Other Land Use (FOLU or previously LULUCF) is an important sink with net removals of 236 million tCO2e in 2000 (AFOLU Working Group 2016). Forests are the largest terrestrial store of carbon, but deforestation is the largest source of carbon dioxide emissions after fossil fuel burning, causing 15% of global greenhouse gas emissions, with a range from 8-20% (van der Werf et al 2009).

5.6.4.1 Objective of Study and Research Questions

The main objective of the study is to arrive at linkages between urbanization and its impact on various ecosystems within the city limits, and also examine the urban growth in this perspective over a time period. The following research questions have been attempted to be answered in the study:-

1. Is there any non industrial (AFOLU) contribution to GHG emissions in Guwahati city?
2. What is the contribution of AFOLU to emissions in Guwahati city?
3. How the different AFOLU sectors have contributed to the emissions in the city?

5.6.4.2 Materials and Methods

The study is confined to the administrative boundary of the Guwahati Metropolitan Development Authority, and the hills and forest ecosystem existing within these boundaries. This also includes, incidentally, the Guwahati Municipal Corporation (GMC) areas. In the instant study, the following components of AFOLU have been selected:

1. Deforestation and conversion of forest to Settlement (in short FS)
2. Burning of Biomass (in short FW)[84]
3. Methane emission from cropland (in short CL)
4. Net CO_2 emission from wetlands (in short WL)

According to Asner (2009), two kinds of measurement are needed to estimate GHG emissions from deforestation, namely the the rate of change in the forest cover which is termed as deforestation rate and secondly the amount of carbon stored in the forest which is termed as carbon stock. The forest activities that release GHGs has been divided into two categories. Firstly, deforestation which is the clear-cutting and often burning of entire biomass, and secondly degradation which includes selective logging, thinning, burning and other disturbances that do not completely remove the forest canopy but lower the carbon-storing capacity of the forests. The loss of forest is best studied using satellite images and other imaging technologies such as Lidar. For carbon stock assessment, IPCC prescribes, as a good practice, in Tier I approach, which is the most general approach, based on generic estimates of forest carbon density values (e.g. tons of carbon per hectare). The Tier II approach is more detailed, and uses forest maps and forest carbon inventories that are more accurate than Tier-1 default values. The Tier-III, is the most rigorous approach, is based on very detailed landscape-specific or even species-specific carbon stock estimates with regular, ongoing reassessments (IPCC, 2000). In the present study,

84 Under Biomass, Fuelwood burning only has been considered in this study. Though this is contributory to energy sector emission, it has been considered here as it is one of the main drivers of deforestation.

guidelines laid down in the IPCC Guidelines for National Greenhouse Gas Inventories, Vol 4, Agriculture, Forestry and Other Land Use, 2006 (IPCC, 2006) have been used within the constraints and limitations of the study.

5.6.4.3 Key Questions

1. What is the relationship between deforestation due to settlements and carbon emission in Guwahati city?
2. What is the contribution of other components of AFOLU to the city CO_2 emissions?

5.6.4.4 Methodology

The contribution of AFOLU (Agriculture, Forests and Other Land Uses) to carbon emission is given by (IPCC, 2006, WRI, 2015):

$$\Delta C_{AFOLU} = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{GL} + \Delta C_{WL} + \Delta C_{SL} + \Delta C_{OL} \quad (5.30)$$

where ΔC= Carbon stock change

FL= Forest Land

CL= Cropland

GL= Grassland

WL= Wetland

SL= Settlements

OL= Other Land

Estimating Carbon Emissions from Deforestation and Fuelwood Consumption

This section is divided into two sub-sections namely carbon dioxide emissions from deforestation and secondly carbon dioxide emissions from fuelwood burning.

CO_2 Emission from Deforestation: The deforestation in Guwahati city is due to conversion of forest land to settlements by the people. Here it can be assumed that the total carbon is lost, as the trees are cut, felled and burnt as firewood and also the soil is dug up to make space for housing etc. Though there are no direct estimates of carbon content of the forests of the Guwahati city, data published by the Forest Survey of India was used (FSI, 2011). The FSI has assessed carbon stocks in various states of the country, and according to its latest available report (2011), the forests of Assam have been found to have an average carbon pool of 61.10 t C ha^{-1}. Therefore, if 100 ha (=1 sq km) of forests are lost to settlements, the corresponding loss is 6110 tC per sq km which translates to 22403.33 tCO_2 ($E_{tCO2} = E_{tC}*44/12$). Therefore, an emission factor of about 22400 tCO_2 per sq km has been used in event of 1 sq km of forested area changing to settlements.

CO_2 Emission from Fuelwood Burning: It has been estimated that 2 metric tonne of firewood is required per family annually in the north eastern region (Mathew, 1987). In 1991 a study on domestic energy of Kamrup district in two blocks namely Dimoria and Hajo was carried out (Borah, 1991). According to Borah, the per capita urban fuelwood consumption was 334.6 kg annually. A nationwide review on fuelwood sampling studies was carried out by Pandey D (2002). According to this study, the share of fuelwood in Assam domestic energy consumption was 44.1% in 1993 and came down to 34.1 % in 1999/2000. According to the study, the per capita consumption of firewood in the forested districts of Assam stood at 435 kg per annum. As per 2011 census details, the % of households in urban area using fuelwood as fuel for cooking comes to 22% in the Kamrup Metropolitan district (Census, 2011).

If	f	= Per capita fuelwood consumption in Kg per annum
	fr	= % of Households using firewood
	P	= Population
	F	= Total quantity of fuelwood in metric tons

Then

$$F = P \bullet fr \bullet f \bullet 10^{-3} \quad \text{tonnes yr}^{-1} \qquad (5.31)$$

$$E_{CO2} = F \bullet NCV_{fuelwood} \bullet EF_{fuelwood} \qquad (5.32)$$

where E_{CO2} = Emission of CO_2 in metric tonnes

$NCV_{fuelwood}$= Net Calorific Value of fuelwood (=0.015 TJ/tonne for fuelwood as default value by IPCC, 1996)

$EF_{fuelwood}$ = Emission Factor for fuelwood (=109.6 tCO_2/TJ for fuelwood as default value by IPCC, 1996) [E_{CO2} = *1.64* $tCO_2 MT^{-1}$ *of wood*]

Estimating Methane Emission from Agricultural Fields of Assam: Methane emissions from agricultural fields across the world vary due to variety of factors such as soil type and texture, organic content and kind of fertilizers applied and the water regime. Therefore, the methane fluxes are largely site specific. However, methane flux studies are not many in the State. Mishra et al (2012) have elaborately dwelt upon the emission factors for methane emission from crop fields of Assam and reported values from literature vary from 6.92 to 46 g m^{-2}. According to Gupta et al (2009), estimated methane emissions from paddy fields of Assam as seasonally integrated flux (SIF) are shown to be in two studies at 9.18 g m^{-2} and 7.14 g m^{-2} at the Assam Agricultural University Titabor farm under National Campaign 2002 (NC-2002). However, the authors reported an average emission factor of 19.0±6.0 g m^{-2} for rainfed floodplain agricultural systems. Another study by Gupta et al (2002) showed that in Jorhat fields, the seasonal integrated flux was 46 g m^{-2}. A study by Gogoi et al (2008) showed wide variation in Ahu and Sali crop methane fluxes. Whereas the Ahu paddy (pre-monsoon crop) methane SIF was found to be 7.51 g m^{-2}, while for Sali paddy (monsoon crop) was found to be 16.39 g m^{-2}. Further as reported by Jain et al (2004) the values for lowland rainfed flood-prone cropping system, the average SIF was found to be 19.0±6.0 g m^{-2}. There being such a wide variation, the value for the lowland rainfed flood-prone (RFFP) cropping system under the Methane Asia Campaign 1998 as reported by Jain et al (2004) and Gupta et al (2009) was used in this study. Therefore, the E_f for methane from rice fields was assumed at 19 g m^{-2} for the city fields. Assuming Global Warming Potential (GWP) of methane to be 21, the formula for estimation of CO_2 emission from agriculture is

$$CO_{2_{eq}} = E_{CH_4} \bullet GWP_{CH_4} \\ = 21 \bullet E_{CH_4} \quad (5.33)$$

$$= 21 * E_{CH4} \quad (5.34)$$

where E_{CH4} is given by

$$E_{CH4} = A * EF_{CH4} \quad \text{Tons yr}^{-1} \quad (5.35)$$

where A is in sq km, and EF_{CH4} is in g m^{-2}. These equations have been adopted from IPCC (1996, 2006) and RTI (2010). The value comes to 399 tCO_2 sq km^{-1}.

Estimating Emissions from Water bodies: The data on emission from freshwater wetland and marshes and their sequestration potential is lacking. As per IPCC (2000a) Special Report on LULUCF, the freshwater wetlands are responsible for 7-40 g m^{-2} yr^{-1} CH_4 emissions, and sequestration rates vary from small negative values to 0.35 tC ha^{-1} yr^{-1}. Assuming an emission rate of 7 g m^{-2} yr^{-1} CH_4 and sequestration rate of 0.35 tC ha^{-1} $yr^{-1}$for 100 ha (=1 sq km) of a wetland, it can be seen that it would emit 147 tCO_2 (=40.09 tC yr^{-1}), while it would also sequester 35 tC yr^{-1}, making it a net source of 5.09 tC yr-^{1} (= 18.66 tCO_2 yr^{-1}). Therefore, for this study, the wetlands have been treated as net source with an emission of 18.66 t CO_2 yr^{-1}per sq km.

Combined Equation for CO_2 Emission from AFOLU: By combining the various parameters and factors for deforestation, fuelwood burning, cropland and wetland, the AFOLU emissions can be estimated as below:

$$CO_2 = E_{FS} + E_{FW} + E_{CL} + E_{WL} \quad (5.36)$$

$$CO_2 = A_{FS} \bullet EF_{FS} + F \bullet EF_{FW} + A_{CL} \bullet EF_{CL} + A_{WL} \bullet EF_{WL} \quad (5.37)$$

$$= A_{FS} \bullet 22400 + F \bullet 1.644 + A_{CL} \bullet 399 + A_{WL} \bullet 18.66 \quad (5.38)$$

where CO_2 = CO_2 Emissions in Tonnes per year

E_{FS} = CO_2 Emissions from conversion of forests to settlements

E_{FW} = CO_2 Emissions from burning of fuelwood

E_{CL} = CO_2 eq emissions from lowland rainfed floodplain cropping system (methane emissions only)

E_{WL} = Net CO_2 Emissions from wetlands (after deducting sequestration)

A_{FS} = Area of forest land converted to settlement (in sq km)

E_{FS} = Emission factor for forest land converted to settlement (= 22400 tCO_2 per sq km)

F = Mass of fuelwood consumed in Tonnes

EF_{FW} = Emission factor for fuelwood

($=NCV_{fuelwood} \bullet EF_{fuelwood} = 0.015*109.6 = 1.644$ t CO_2 per tonne fuelwood)

A_{CL} = Area under cropland in sq km

EF_{CL} = Emission factor for cropland in RFFP cropping system

($=GWP*EF = 21*19$ g m^{-2} $=399$ g m^{-2} or ton km^{-1})

A_{WL} = Area of wetland in sq km

EF_{WL} = Emission factor for wetland (net emission = 18.66 tCO_2 yr^{-1} per sq km assumed)

Rates of Change with Baseline Year: Changes in various parameters such as loss of forest areas, increase in built up areas etc. over consecutive time periods were computed by simple ratio of value difference and time difference. However, to arrive at long term perspective, the differences were computed from the base year 1911. Assuming values V_{t0} , V_{t1}, V_{t2} for a particular component in year t_0 (1911), t_1 and t_2, the rate of growth or decline were computed as below:-

$$R = (V_{t2}, - V_{t2}) / (t_2 – t_1) \quad (5.39)$$

$$R_0 = (V_{t2}, - V_{t0}) / (t_2 – t_0) \quad (5.40)$$

5.6.4.5 Data Sources

The secondary datasets used in the study were obtained from the related departments of the Govt of Assam. Inputs from the Forest Department included working plans for the forest areas of Kamrup district since the year 1938–39 till the year 2011–12, stock maps of the forests, data and maps concerning the hills of Guwahati. The master plan, GMDA boundary and other secondary data pertaining to the city and urban sprawl were obtained from GMDA.

The mapset studied included the Survey of India topographic sheets 78N12, 78N16 firstly on 1=1 Mile scale and survey year 1911-12, and secondly on 1:50000 scale and survey year 1967-68, 78N12 (NE, NW, SE & SW) and 78N16 (NE, NW, SE & SW) on 1:25000 scale and survey year 1986-87. The satellite imagery for the study area was obtained from USGS for the year 2010 (Landsat TM 5 P137 R42 DoP 30.01.2010) and 2015 (TM 8 P137 R42 DoP 28.01.2015). The results were refined by cross checking from available Google Earth satellite data in the public domain. The land use land cover map of Guwahati city available in the Microzonation study of Guwahati city by AMTRON and other agencies under the aegis of the Department of Science and Technology, Government of India, based on satellite data of 2003 was also used. The population figures for the Guwahati City were taken from various sources such as Census 2001, 2011, GMDA Master Plan and the Statistical Handbook (2014), Government of Assam. The formulae used for the population projections are given in Appendix-3.

GIS & Remote Sensing: The mapsets and satellite data were brought on a single Coordinate Reference System (CRS) using the EPSG:32646-WGS 84 / UTM Zone 46N projection system on the QGIS platform. The required features of built up area, hills and forests were extracted digitally within the GMDA boundary vector. The forest cover was computed only within the hill vectors using unsupervised classification and quick reconnaissance type ground truthing. The agricultural areas and wetlands were computed for all the areas falling within the GMDA boundary. However, there would be some overlap between agricultural areas and wetlands as some of the shallow areas of the wetlands are used for rice cultivation.

5.6.4.6 Results, Analysis and Discussion

Based on the primary and secondary data, the population growth trend, built up area, value of forest ecosystem services, forest loss and carbon footprint estimation were computed. The results and findings are discussed below:

Loss of Forests to Settlements: A detailed account of loss of forest ecosystem and ecosystem services values has been presented at length by Yadav & Barua (2016) for the Guwahati city. The **Table No. 5.12** adopted and modified from Yadav and Barua (2016), depicts the land use change pattern of the hills/forests of the city since 1911. The forest areas from 1911 to 2015 have also been shown in **Map No. 5.6**.

Table No. 5.12: Loss of Forest Cover in Guwahati City (1911 to 2015)

Year	Dense Forest (Ha)	Degraded Forest (Ha)	Total Forest Area (Ha)	Forest Converted to Settlement (Ha)	Rate of Forest Loss (Ha yr^{-1})	Cumulative Forest Loss (Ha yr^{-1})
1911	6708.63	0	6708.63	172.63	0	0.00
1967	6158.44	0	6158.44	722.82	9.82	9.82
1986	5619.44	0	5619.44	1261.82	28.37	14.52
2003	2334.21	2562.31	4896.52	1984.74	42.52	19.70
2010	1722.84	1500.62	3223.46	3657.80	99.83	35.20
2015	1438.49	983.27	2421.76	4459.50	160.34	41.22

Fuelwood Consumption in Guwahati City: The fuelwood consumption from 1911 to 2015 has been estimated based on the methodology suggested earlier in this study. The values are tabulated in **Table No. 5.13**

Table No. 5.13: Fuelwood Consumption of Guwahati City

Year	Population [P]	Fraction of Population using Fuelwood [fr]	Per Capita Per Year Fuelwood Consumption (Kg Yr^{-1}) [f]	Fuelwood Consumption (Metric Tonnes) [$F=P*fr*f*10^{-3}$]	Per Capita Fuelwood Consumption (Metric Tonnes) [F/P]
1	**2**	**3**	**4**	**5**	**6**
1911	13785	1[$]	435[*]	5,996.48	0.435
1967	255724	1[$]	435	111,239.94	0.435
1986	557932	0.46[%]	435	111,642.19	0.200
2003	906394	0.34[%]	435	134,055.67	0.148
2010	963255	0.22	435	92,183.50	0.096
2015	1097751	0.22[&]	435	105,054.77	0.096

$ Assumed to be 100% dependent upon fuelwood
% As per Pandey D (2002). 1983/1984 NSSO value for all India used in 1986
& As per 2011 household census data for Kamrup Metropolitan District
* As per Pandey D (2002)

Status of Croplands in Guwahati City (1911-2015): The areas of cropland (agricultural areas) was estimated within the city limits of GMDA from 1911 to 2015 based on the available topographic sheets, satellite images and land-use land cover maps available from various sources. The finding are presented in the **Table No. 5.14.** The **Map No. 5.7** depicts the agricultural areas from 1911 to 2015 pictorially.

Table No. 5.14: Agricultural Area of Guwahati City

Year	Agricultural Area in Sq Km
1911	74.57
1967	58.32
1986	52.49
2003	42.26
2010	16.51
2015	14.41

Status of Wetlands in Guwahati City (1911-2015): The wetlands of the Guwahati city were classified in three categories namely:-

1. Marshy lands and swamps (dry water bodies during pinch period)
2. Waterbodies (retaining water even during drier periods)
3. Important Man made ponds and tanks

These were delineated within the city limits of GMDA from 1911 to 2015 based on the available topographic sheets, satellite images and land-use land cover maps available from various sources. The finding are presented in the **Table No. 5.15** . The wetland areas from 1911 to 2015 have been depicted in **Map No. 5.8,** and the wetland status of Guwahati city shown in **Chart No. 5.11A.** The chart shows that the loss of wetlands have been very high since 2010.

Table No. 5.15: Yearwise Area of Wetlands in Guwahati City

Year	Marshy Land (SQ Km)	Water bodies (Sq Km)	Ponds/ Tanks (Sq Km)	Total Wetland Area (Sq Km) [W]	Loss of Wetlands (Sq Km Yr^{-1}) [$\Delta W/\Delta T$]	Loss of Wetlands with 1911 Baseline (Sq Km Yr^{-1}) [$\Delta W/\Delta T_0$]
1911	17.71	9.25	0.18	27.14	0	0
1967	9.88	7.83	0.16	17.87	0.17	0.17
1986	6.90	7.88	0.16	14.94	0.15	0.16
2003	6.65	6.51	0.16	13.32	0.10	0.15
2010	6.61	6.02	0.16	12.79	0.08	0.14
2015	6.01	5.73	0.16	11.90	0.18	0.15

AFOLU Contributions to CO_2 Emissions in Guwahati City (1911-2015): The CO_2 emissions arising out of the various components of the AFOLU, namely forest area lost to settlement, fuelwood burning, emissions from agricultural activities (only cropland CH_4 emission for a lowland rainfed floodplain system), and net emissions from wetlands were computed from the **Eq No. 5.38**. The total AFOLU emissions, thus arrived, along with per capita emissions are given in the **Table No. 5.16**. To understand individual contributions of the various components of the study, component-wise emissions along with per capita emissions have been computed as well based on the Eq No. 5.38 and presented in the **Table No. 5.17**.

Table No. 5.16: Yearwise Area under AFOLU Emissions

Year	Population	Forests to Settlements (Sq Km)	Fuelwood Consumption (Metric Tonne)	Area under Cropland (Sq Km)	Area under Wetlands (Sq Km)	AFOLU Emissions (tCO_2)	Per Capita AFOLU Emissions (tCO_2)
1911	13785	1.7263	5,996.48	74.57	27.14	78787.2	5.72
1967	255724	7.2282	111,239.94	58.32	17.87	368393.28	1.44
1986	557932	12.6182	111,642.19	52.49	14.94	487409.73	0.87
2003	906394	19.8474	134,055.67	42.26	13.32	682079.57	0.75
2010	963255	36.5780	92,183.50	16.51	12.79	977723.03	1.02
2015	1097751	44.5950	105,054.77	14.41	11.90	1177609.69	1.07

Table No. 5.17: Yearwise AFOLU Emissions and Per Capita Emissions

Year	Population	E_{FS}	E_{FW}	E_{CL}	E_{WL}	$\overline{E}_{FS}$	$\overline{E}_{FW}$	$\overline{E}_{CL}$	$\overline{E}_{WL}$
1911	13785	38669.12	9858.21	29753.43	506.43	2.81	0.72	2.16	0.037
1967	255724	161911.68	182878.46	23269.68	333.45	0.63	0.72	0.09	0.001
1986	557932	282647.68	183539.76	20943.51	278.78	0.51	0.33	0.04	0.000
2003	906394	444581.76	220387.52	16861.74	248.55	0.49	0.24	0.02	0.000
2010	963255	819347.20	151549.67	6587.49	238.66	0.85	0.16	0.01	0.000
2015	1097751	998928.00	172710.04	5749.59	222.05	0.91	0.16	0.01	0.000

Discussion: The population of the city has grown from a modest 13785 in 1911 to 1097751 in 2015, indicating a growth of about 80 times over a century. The built up area has grown from 8.59 sq km in 1911 to 176.19 sq km in 2015, indicating a growth of 20.5 times during the period. Taking 1911 as baseline, the built up growth rate has been steadily on the rise, and is currently at 1.61 sq km per year. This rise in built up and population growth appears to have come from the areas covered by hills and forests, wetlands and agricultural open fields. Almost a quarter of the city built up is on forest areas (Yadav R & Barua A, 2016). The fuelwood scenario of the city is such that as of 2011 (Census,2011), only 22% of the population (in terms of households) depended upon fuelwood as a means of cooking energy. This amounts to about 0.1 MT of fuelwood being consumed annually in the city. Assuming higher levels of fuelwood use in the past among the city households, collating from scanty data available in the literature, it is seen that fuelwood consumption, has remained almost more than 0.1 MT per annum since 1967. At this rate in the past 50 years, the city households have consumed almost 5 MT of fuelwood. The changes in AFOLU components over time has been depicted in **Chart No. 5.11B**. Carbon emissions from agriculture were very significant and contributed almost 2.16 tCO_2 per capita in 1911 towards the total AFOLU emissions of 5.72 tCO_2 per capita. As the area of the agricultural fields dwindled rapidly by 5 times in the last 100 years, the cropland emissions also got dropped proportionately. In 2015, the per capita cropland contribution dropped to just 0.01 tCO_2 per capita showing more than 200 times drop. The CO_2 emissions from wetlands have been very low, amounting to just 500 tCO_2 in 1911 which dropped to 222 tCO_2 in 2015. The CO_2 emissions from fuelwood have been of the order of 0.1-0.2 MT since 1911. The per capita emission from fuelwood, however, dropped from 0.72 tCO_2 per capita in 1911 to 0.16 tCO_2 per capita in 2015. Fuelwood burning is the second largest contributor of AFOLU emissions in Guwahati, after deforestation. Deforestation and conversion of forest land to settlement is the largest contributor to AFOLU emissions in the city which contributed to almost 50% in 1911, but its share increased to 85% in 2015. Due to increased urbanization activities, the per capita contribution of deforestation and loss of forests to settlements stands at 0.91 tCO_2 per capita in 2015. The contributions of various components of AFOLU to CO_2 emission have bee depicted in **Chart. No. 5.11C**. The vertical bars indicate total emissions, while the lines show the per capita emission from various components. It is seen from the Chart that while all other contributors to AFOLU emissions have come down in course of time due to shrinkage of area, the one to continue increasing is conversion of forests to settlements; and fuelwood increased, but since 2003 showing a decreasing trend possibly due to adoption of LPG by households.

5.6.4.7 Conclusion

Yadav R and Barua A (2016) in the study on carbon footprint of the Guwahati city had assumed an average of 1.80 tCO_2 per capita emission within the city for 2015. The present study reveals that almost 1 tCO_2 per capita is contributed from the AFOLU sector alone. Further, almost 85% of this contribution comes from loss of forest areas to settlements. Guwahati is a very fast growing city, and has already crossed 1 million population mark, and also is selected as one of the 100 smart cities under the SMART city mission programme. The planners would have to ensure that the rapid decline of forests and wetlands is put to halt.

5.6.4.8 Limitations of the Study

The study has the following limitations:

1. The study does not take into accounts the enteric fermentation of livestock, emissions from landfills, N_2O release from synthetic fertilizers

2. It has been assumed that forest areas lost to settlements contribute entirely to carbon emission inclusive of above ground and below ground biomass. However, some trees may be either standing originally or planted afresh by residents. These have not been taken into account.

3. The emission factors have been taken from published literature. However, there are no specific publication on emission factors pertaining to Guwahati city per se.

4. The estimates of AFOLU, including fuel-wood, in area and value may be considered as upper limits, as satellite data of coarse resolution has been used prior to 2010.

5. The carbon sequestration for the city forests also required to be worked out in order to arrive at the actual mitigation potential.

5.7 Combined CO_2 Emission and Entropy Footprint of Guwahati City

The CO_2 emission was converted to its entropy value at 298K with a factor 4.86 per tonne of CO_2, taking molar entropy of CO_2 to be 213.69 JK^{-1} $Mole^{-1}$ from standard thermodynamics textbooks. All energy was expressed in TJ, entropy was expressed in TJK^{-1} and all CO_2 emissions in Million Tonnes ($MtCO_2$). Per capita entropy was reported in MJK^{-1}, and CO_2 emissions in tCO_2.

5.7.1 Summary of Entropy Generation and CO_2 Emissions for Sectors Studied

The Case Study culminated in tabulating the entropy generation and CO_2 emissions from direct and indirect sources for Guwahati city. The tabulation has been provided at **Appendix 5: Part I**.

5.7.2 Average Values of Entropy and CO_2 Emission from Energy Sources (2010-2015)

Taking a common dataset of 6 (six) years from 2010-11 to 2015-16, the total energy intake, entropy generation and CO_2 emission were worked out and the findings are given below. For this only three sector were taken namely: Electricity consumption, Fossil fuels consumption and building materials. The compiled tables are shown in **Appendix 5: Part II**. From the study it is evident that the Guwahati city on an average uses 50420 TJ (= 50PJ) of energy per year directly and indirectly in the three sectors namely electricity consumption, fossil fuel consumption and building materials and emits 6.3 $MtCO_2$ per annum, and generates 143.76 TJK^{-1} of entropy in these sectors. In these sectors total waste heat generated from input energy (directly and indirectly) is 42841 TJ (=43 PJ). On the other hand, the floors built up annually in the city add to about 22815 TJ of energy release (as waste heat) during the life time of the constructed space and would account for 77 TJK^{-1} of entropy on this account, taking the total entropy to 220 TJK^{-1}. The amount of energy released by the constructed space over its life time almost equals the direct and indirect energy consumed in electricity and fossil fuels usage in a year.

5.7.3 Per Capita Emission and Entropy Values from all sources studied for 2015

The per capita emissions and entropy generations were calculated only for 2015 from all sources including AFOLU and given in Table No. 5.18.

Table No. 5.18: PER CAPITA ENTROPY GENERATION & CO_2 EMISSION

Sl. No.	Process	Entropy (ΔS MJK^{-1})		CO_2 Emission (tCO_2)		Total Entropy (ΔS MJK^{-1})
		Direct	**Indirect**	**Direct**	**Indirect**	
1.	MS, HSD, LPG & KOIL	20.48		0.77		24.22
2.	Fuelwood (Annual for 2015)	4.38		0.16		5.16
3.	Forest to Settlement (5 Yrs)			0.91		4.42
4.	Cropland (5 Yrs)			0.01		0.05
5.	Electricity	9.69	22.03		1.20	37.55
6.	Building materials	50.41	39.76		5.67	117.73
	TOTAL	**84.96**	**61.79**	**1.85**	**6.87**	**189.13**

The Per Capita CO_2 Emission for Guwahati for 2015 comes to 8.72 tCO_2. The total emissions and entropy generation can be summed up in the total per capita entropy value of 189 MJK^{-1} for 2015. AFOLU contributes directly (as an average of 5 years from 2010 to 2015) along with fuelwood 0.344 tCO_2 annually [*(0.91+0.01)/5 + 0.16=0.344*].

5.7.4 Share of Energy, Entropy & CO_2 Emissions in the Sectors Studied

Broadly the study focused on four sectors in the city, namely electricity, fossil fuels, building construction and AFOLU. Ignoring AFOLU, the share of the other three sectors to the total energy consumed and emissions in the city is given in Table No. 5.19 as % of total energy consumed, total entropy and CO_2 emitted as an average of 2010-11 to 2015-16. See Chart No. 5.12A, 5.12B & 5.12C. Over the years as construction activities in Guwahati have increased, the indirect (embodied) energy and emissions from building sector seem to dominate the total share more and more, as is evident from Chart No. 5.12D.

Table No. 5.19: Sectoral Share of Energy Input and Emissions

Entity estimated	Electricity	Building Construction	Fossil Fuels	Total
Energy Input (%)	19.89	55.72	24.39	100
Entropy (%)	26.18	53.41	20.41	100
CO_2 Emission (%)	17.77	68.54	13.69	100

5.7.5 House Hold (Building) Energy Usage

The Case Study focused on four sectors namely electricity consumption, building construction (floor space), fossil fuel consumption and AFOLU. As per the ISIC (See Section 3.6.2.4), household energy consumptions falls under code 9820 Undifferentiated Service Producing Activities of Private Households for Own Use. This would include lighting, fan, comfort cooling and heating and energy used in cooking. As illustrated in Fig No. 5.2, it can be seen that the present Case Study covers four segments under Code 9820, providing energy services namely electricity consumption, LPG, Kerosene and Fuelwood. While there is continuous data for electricity consumption, LPG and Kerosene (assuming that these are used entirely at household level) for the period 2010 to 2015, in case of fuelwood, data was generated based on population projections as explained in the AFOLU section. The following tables are produced for building energy use in Guwahati city from 2010-2015. The subsequent tables provide the associated entropy generation and CO_2 emission at household level. The data is averaged at the end of the each table over the 2010-2015 period. The Tables are provided in Appendix 5: Part III. It is seen that the growth in energy consumption at building/household level (combining all the four components – Electricity, LPG, Kerosene & Fuelwood) has grown by 26.75% while entropy generation and CO_2 emissions have gone by about 30% during the period. At the same time, per capita energy consumption for all the 4 components have grown by 11%, while emissions have gone up by about 14% during the study period of 2010-2015. The trends in household energy consumption are shown in Chart No. 5.12E. While contribution of fuelwood has remained almost constant all throughout in energy value terms during 2010-2015 (as there are no intermediate data points), and so has kerosene use, while electricity and LPG have grown steadily during this period. The average efficiency of energy use in buildings is 11.74%, and average annual energy consumed is 19006 TJ. The average per capita energy used is 18593 MJ.

5.7.6 Trends for Guwahati City

Chart No. 5.12F shows total energy usage (direct and embodied), waste energy and entropy generation. Chart No. 5.12G shows total input energy (building embodied energy not taken into consideration), waste energy and entropy, while Chart No. 5.12H shows the same along with CO_2 emission. As shown in these charts clearly, the energy consumption is on the rise. It rose from 36002 TJ in 2010-11 to 64335 TJ to 2015-16, showing a growth of 79%. Similarly, CO_2 emission rose from 4.19 $MtCO_2$ to 8.39 $MtCO_2$ showing 100% growth. Entropy generation (from input energy) rose from 101.26 TJK^{-1} to 185.01 TJK^{-1}. Taking input energy and waste energy into consideration, and assuming the city as an organic unit, this study shows that the efficiency of the overall system is 15%.

5.7.7 Case Study Conclusions

The case study is an instrumental case study designed to help in understanding the relationship between entropy and the development process. Urbanization is a growth engine where energy use would rise in order to provide better QoL and higher living standards. As the city grows, there is a life style shift in the population due to higher use of appliances, gadgets, vehicles, comfort cooling/ heating etc, and thus, energy consumption goes up. In the instant case study of Guwahati city in which energy use (direct and indirect) as well as consequent CO_2 emission and entropy generation have been studied spanning over 4 sectors, it is found that the per capita energy use has been steadily growing. It is seen that the average total energy inflow into the city (input energy) from 2010-2015 is 50420 TJ, and the average energy use in buildings is 19006 TJ per annum (Table No. A5.10, A5.11 & A5.15). The average efficiency of input energy use comes to 15.03%, that for total energy comes to 10.34%, and for building energy usage comes to 11.74%. It is also seen clearly that from 2010 to 2015, the CO_2 emission has almost doubled. The city efficiency levels are found to be 15%.

As can be seen, the QoL in Guwahati city shows an upward trend which is indicated by rise in per capita power from 23 W in 2001 to 117W in 2015. This is a five fold increase in 15 years time span. The city is also seem to be adding 1.8 million m^2 of built up space annually (2010-2015), and growing at the rate 6.7 sq km per year. At the same time the CO_2 emissions have gone up from 4 $MtCO_2$ in 2010 to 6 $MtCO_2$ in 2015. Similarly entropy generation has gone up from 81 TJK^{-1} in 2010 to 113 TJK^{-1} in 2015. It is, thus, seen that there is a direct relation positive relation between improvement in QoL and development and emissions indicating the entropic nature of the development process.

CHAPTER 6

6 Conclusion, Policy Implications and Future Research

> *It is indeed a disease of the mind to throw away a coat or a piece of furniture while it can still perform its specific service. To get a "new" car every year and to refashion the house every other is a bioeconomic crime* (NGR, 1975 p378)

6.1 Concluding Discussion

An extensive literature review was conducted for investigating the thermodynamics economics relationship centering around the foundational works of NGR. Going beyond the historical review, literature on application and use of NGR’s theory on entropy and economic process was studied to find out the relevance of NGR’s work in the present day context of climate change and global sustainability. The review reveals that almost all new approaches and pathways of development which attempt to combat climate change and usher in sustainable development in the true sense derive their strength from the works of NGR, such as the degrowth movement, circular economy, natural step to mention a few. After a gap of almost forty years, there seems to be resurgence of NGR's theories, particularly the thermodynamic basis of all economic activities. Two of the most neglected streams of his theory namely the threat of **thermal pollution** that would be larger than the resource scarcity, which has been held as the most imminent threat (Mayumi, 2009), and secondly the lack of appropriate approaches for applying the theories of NGR in real world economic processes (Glucina & Mayumi, 2010) are the central to the this study This study has made a bold attempt to address both the issues within the limitations of the research by designing a real world case study to move beyond economic process and to take it a step forward to investigate the entropic nature of development process, and in doing so, also examine the frontiers of sustainability in a manner that it may not be termed “snake oil”. Quoting the desperation of Mayumi (2009), in his article “*Nicholas Georgescu-Roegen:His Bieconomics Approach to development and Change*”, which is very pertinent here “As the last student of Georgescu-Roegen, I do hope that this article will trigger a more systematic investigation of his work and a fruitful discussion on this truly profound thinker.” Literature review revealed that while there is no dearth of research on “Shanon's Information Entropy” and carbon emission in city case studies, but there are studies few and far between in case of thermodynamic entropy and city systems or their linkage with global warming. There have been some studies on Anthropogenic Heat Flux (AHF) such as by Flanner (2009), Ming Cai et al (2003) Bennewitz (2007) who have raised concern over serious lack of accommodation of anthropogenic heat in the current climate change models. *In conclusion, it can be said that just as the standard economists are not accommodative of ecological economic theories and premises, so is the case with thermal pollution which appears to be a very weak candidate in comparison with* CO_2 *emissions!*

6.1.1 Development Paradox and Re-emergence of NGR

The revolutionary science based on The Entropy Law and Economic Process by NGR appears to be getting into prominence since the last decade and a half after being virtually dormant for nearly thirty years. His criticism of NCE on growth and development seem to be justified in today's world of impending environmental cataclysm. NGR's treatment of the economic process in the light of the impeccable 1st and 2nd laws of thermodynamics, especially his criticism of NCE production function, scarcity and substitution, pollution and waste which were examined in some detail in Chapter 2, were well founded, have stood the test of time and have become relevant today. His theories are foundational to the new interdisciplinary science of ecological economics. Based on these concepts, a theoretical framework for the research study was developed, which depicts the economic process as a sub system of the large earth system (thermodynamically a closed and non equilibrium system which must throw away all the energy it receives from the sun, else it would get hotter and hotter), which in turn is a part of the larger sun-earth-space universe. This has been developed taking the systems approach and applying the laws of thermodynamics on economic process, an approach which NGR vigorously advocated and criticized the NCE for following classical mechanical predictive, reversible and unrealistic models to economic processes. Though there is no rebuttal of application of the thermodynamic laws to economic processes, and whatever criticisms were there, except for the 4th Law of Thermodynamics by NGR, in the past now seem to have settled down. However, there remains a gap as to the actual manner of application of these laws to the economic thought because of which various approaches have emerged ranging from metaphors, analogues to highly arithmomorphic treatments, the main reason being the difficulties of application of entropy and its estimation in real world processes. These issues have been dealt at some length in Chapter 3.

We have entered an era of high consumption of energy and also are moving towards urbanization with high standards of living, characterized by high resource use, and now serious questions on the sustainability of the existing economies are being raised world wide, while at the same time rising CO_2 in the atmosphere, global warming, frequent economic meltdowns and resource crisis such as peak oil and peak phosphorus have pushed countries to rethink on their economic agenda. As the North is moving towards degrowth, but the South is yet to agree on any such agenda as there is need for “development” in these countries. These issues have been dealt with in Chapter 4, and a growth and development paradox, coupled with the complexities of rebound effect with Jevons' paradox superimposed, has clearly emerged in the study. While sustainable development was found to be the most oft repeated catchword with as many as 37 definitions in literature, NGR considered it a snake oil. Even Daly was critical about the definitions of sustainable development. NGR predicted, applying the entropy law that even zero growth is unsustainable (unless we go back to "berry picking economy" according to NGR). It is the entropy law that has brought to the fore the biophysical limits of source and sink, which is foundational in understanding sustainability and climate change. While NGR predicted in 1975 about the impending "thermal pollution" that would prove a "more crucial obstacle" and further emphasized on "continuous accumulation of carbon dioxide in the atmosphere which could cause green house effect heating of the globe" (NGR, 1975, p 358), the concern of mankind today, after 45 years, about the threat of 2^0 C rise in global surface temperature is a fast turning into a reality. The IPCC (2007, 2014) today and the CoP are seized of the matter, and all Business As Usual (BAU) economic pathways are under revision. We have lost precious 45 years in realizing that the entropy law still remains unbeatable, and that our economic processes are not beyond it.

6.1.2 The Case Study and Its Significance

With this backdrop, the theoretical framework, developed in Chapter 2, was further refined in Chapter 4 with a "new process" approach of NGR which is a low entropy process. In order to test the basic principle of the framework that all development processes are function of various economic processes which in turn are functions of a large number of physical and chemical processes, which NGR called elementary processes, and further that the framework links economic process and development process to QoL and well being, a case study of urbanization was formulated for Guwahati city and 4 sectors namely electricity, fossil fuels, buildings and AFOLU were studied from the waste heat and CO_2 emission perspective. The Thesis through the case study brings to fore the "thermal pollution" due to economic process which is comprised of waste heat and CO_2 emission.

It was found from the case study of Guwahati city that development process, which was seen in terms of population growth, built up area growth, electricity, fossil fuel consumption and impact of development on the city ecosystems namely forest, wetlands and agriculture, that the growth of the city has resulted in increase of energy consumption, increase in entropy and CO_2 emissions and accompanied reduction in the ecosystem. Guwahati city shows an upward trend in QoL which is indicated by rise in per capita power from 23 W in 2001 to 117W in 2015, which is a five fold increase in 15 years time span. The city is also seem to be adding 1.8 million m^2 of built up space annually (2010-2015), and growing at the rate 6.7 sq km per year. At the same time the CO_2 emissions have gone up from 4 $MtCO_2$ in 2010 to 6 $MtCO_2$ in 2015, and entropy generation has also gone up from 81 TJK^{-1} in 2010 to 113 TJK^{-1} in 2015. The city is seen to use on average in last 6 years (2010-2015) about 50420 TJ of energy, of which 42841 TJ dissipates as waste heat and CO_2, giving an efficiency of 15% to the city metabolism. Sector wise finding are given in Chapter 5 at the end of each of the sectoral studies. The policy implications emerging out of the case study are discussed Section 6.2 of this Chapter.

6.2 The Case Study: Sectoral Policy Implications

The case study looked at entropy generation and CO_2 emission of the Guwahati city in four different sectors. Policy implications for each of the sectors are given separately.

Electricity Consumption Sectoral Case Study: Given the present growth rates and demand of energy, the city is likely to touch a consumption level of almost 2 TWh by 2025 in the Business As Usual scenario. Policy level interventions are needed to decouple the development process and energy input as a long term policy measure. The following are some of the policy implications of the electricity sectoral case study:

1. There are three pathways available to the policy makers to reduce emissions and entropy from electricity. Firstly, to invest substantial public funds in improving the efficiencies in the electricity system. Secondly, to launch awareness campaigns and promotional schemes for adoption of low wattage appliances and systems; and thirdly, substitute thermal power by renewable energy. A 30 W per capita drop for Guwahati would be equivalent of investments in efficiency on day one, and a 50 W per capita drop would compensate for efficiency improvements till 2025. Substituting green power by 30% would help contain emissions by 2025-26 at the current levels. The analysis above suggests that the policy makers need to draw up strategies to reduce per capita wattage by 30W immediately, 50W by 2022 and 75W by 2025. Additionally, 20% substitution by renewable energy should be made by 2020-21, and 30% by 2022-23.

2. The policy makers should, therefore, actively promote low wattage housing to keep below 100 W in the future, and preferably to be run by renewable energy sources. This would help the city reduce carbon emissions in the long run.

Fossil Fuels Sectoral Case Study: The following policy implications are suggested for the fossil fuels sector for the city:

1. While LPG should completely replace Kerosene and fuelwood as cooking energy, the use of kerosene is also for lighting purposes which should be replaced by solar powered energy. Additionally, LPG substitution goal should be pursued at household level by conversion of household organic waste to energy (through bio-digesters). Stakeholder awareness and concessions by the city authorities can make a huge impact on reduction in consumption of LPG by households. The city authorities should mandate compulsory biodigester installations within a year or two by all commercial establishments and educational institutions and service sector.

2. Consumption of fossil fuels is mostly in transport sector. The number of private vehicles is increasing. This trend would never allow the consumption of fossil fuels to drop. Therefore, the city authorities need to focus on strengthening public transport, incentivising Electrical Vehicles, initiate Mass Rapid Transport System for the city, restrict registration of new vehicles, increase road tax and prescribe high parking fees, so that public transport is strengthened. Additionally infrastructure for supporting EV, such as solar charging stations maintenance workshops etc. should be provided.

3. To promote zero carbon life styles and well being, it is suggested that the city authorities should create cycling lanes, walk ways and no vehicle zones.

Building Sectoral Case Study: Some of the policy implications of the building sectoral case study are enumerated below:

1. It is no denying that the current rate of 1.86 million sq m per annum of floor space would grow further as the business and commerce activities of the city increase. The city authorities need to frame green building guidelines and incorporate them in their bye-laws so that carbon footprint can be reduced or minimized. The city authorities should actively promote low wattage housing and green buildings with alternate sources of energy.

2. The city authorities may incentivise construction activities that incorporate input of low carbon construction materials. For each such permission, amount of proposed material substitution, recycling, energy savings, carbon footprint reduction should be documented and its implementation monitored. The low carbon agenda in building sector cannot be successful without involving the stakeholders namely builders. Often there is danger in introduction of new materials by way of lack of local skills availability, high import and

transportation costs, lack of local resource availability etc. Therefore, any introduction of alternate building materials should be carefully screened by the authorities. It is suggested that prototypes and demo buildings may be constructed for demonstration purposes to win the confidence of the stakeholders.

3. The Government must come with a comprehensive Brick Kiln policy to modernize all the existing brick kilns, and promote alternate technologies of brick manufacturing or building construction by materials which do not require use of bricks. There is a big scope for recycling and substitution in the brick making industry. The Government should actively promote new technologies in all the government and public buildings.

AFOLU Sectoral Case Study: A suggested programme for the policy makers, as it emerges from the AFOLU sectoral case study, is listed below:

1. Total halt on fragmentation of forest areas and total arrest of deforestation is the call of the day. The forests of the city should be restored to the extent possible. The city authorities need to adopt massive afforestation drive planting at least a million plants a year, and removing encroachment from the forest areas. Afforestation on hill slopes would help in building resilience by future-proofing and reducing soil erosion, landslides which aggravate urban flooding. However, the Land Use cover of the city should be regularly monitored, and violators should be penalized heavily.

2. Wetland areas should be freed from encroachment, and improvement programme should be taken up so that wetlands become sinks. Agricultural areas within the existing city limits should be converted into green spaces, so that the remaining 10-12 sq km of croplands could become sinks of the future, giving the much needed relief to the city dwellers.

3. The number of households using firewood is 22% now, which could be brought to 8-10% level in next 5 years.

4. The AFOLU emissions should be reduced from 1 tCO_2 per capita to almost 0.1 tCO_2 per capita. The forests and wetlands and the croplands converted to forest lands would become sinks sequestering the CO_2 for the citizens. This would help in achieving the SDG 11 "**Make cities and human settlements inclusive, safe, resilient and sustainable**", especially the Targets 11.5, 11.6, 11.7 and 11.b.

6.2.1 Summarizing the Research and Policy Implications

Two expected research outcomes were framed with the objective of carrying forward the work of NGR and link entropy to development process, and secondly to mainstream concept of entropy in climate change and sustainability debate by conducting a real world case study.

It was proposed that a development process is a function of a set of economic processes, which in turn are functions of a number of physical, chemical and biological processes. Each of these processes in the end depends upon energy and matter input to produce useful goods and services (in form of energy and matter) and generates waste in form of energy (waste heat) and waste matter. The study proposed, thereafter, to take two measurable parameters namely CO_2 emission and entropy in an urban development process comprised of seven economic activities (as per UNISIC classification) in the city under four study sectors i.e. Electricity, Fossil Fuels, Building and AFOLU, and thereafter broken down into 20 physical and chemical processes, out of which 12 processes, namely agricultural fermentation, logging and deforestation, combustion of fuels, calcination and clinker formation, heat of hydration, heat of carbonation, baking of clay, steel manufacturing, thermal power generation from coal, grid transmission, distribution and household electricity consumption were studied. The energy input (direct and indirect) was worked out from the available datasets, and resultant entropy generation and CO_2 emission were calculated accordingly as per methodology already outlined. It was found through literature review and city case study that entropy and development process are intrinsically coupled through exchange of energy and matter, and improvements in QoL are accompanied by generation of large amounts of emissions and waste heat. The city is an engine of development transforming energy and matter to provide improved QoL and in process and generating waste (waste heat and CO_2). In the case study, it was found that Guwahati city currently (2015) uses almost 64 PJ of energy annually (*36 PJ in 2010*), of which 55 PJ goes as waste (*30 PJ in 2010*). Therefore, development and entropy are directly linked. Entropy generation appears to be rising as development progresses. Though from the city case study, the result holds good, but further studies are required to be conducted to triangulate the results and to form a firm relationship. As entropy generation rises due to development process, issues about its sustainability arise. The more is the development, the more shall be the entropy generated. This places automatically limits on the source as well as the sink. Given the present day development approach based on the pattern of the industrialized nations, the Thesis, in no way, talks against development, but suggests new approaches to development, improvement in QoL and well being keeping in environmental health of the earth system in mind and scarce resources. When talking of entropy reduction or minimization, we need to also consider reduction of entropy within the system by self organizing entities. Any entity that reduces its own entropy, does so at the cost of the environment (i.e. entropy rise in the surroundings). However, such a behaviour of entropy reduction would not bring sustainability. The waste heat and CO_2 emissions released in a development process impinge upon the the climate stability that again adversely impacts sustainable development. Sustainable development does not appear to be possible unless the existing economic processes are replaced by newer process that are low in entropy production and work at near normal temperature and pressures. The following are some of the emerging policy paradigms from the study:

1. The earth is a closed thermodynamic system of which the economy is only a sub system. The earth can receive energy from the sun, but being a closed system, must radiate back all the heat to space, else the plant would get hotter. This implies that the sum of the energy budget of the earth must always be zero. NASA studies are already showing that the earth has developed tendency to retain a part of the heat (0.6 Wm^{-2}). NGR opined in 1975 that such a situation was not at all good for the planet, and the challenge of the thermal pollution would be more challenging than the impending resource crisis. The question is if NGR was right 45 years ago, then, what are we doing today to allay thermal pollution? Despite global agendas and agreements, solutions of reducing the GHG emissions are not in sight mainly due to our Business As Usual (BAU) approaches. Policy makers need to address through effective policy interventions and regulations to help shift away from BAU pathways.

2. The case study and analysis of urbanization in this Thesis clearly show that the world is moving rapidly towards urbanization, and humanity is moving towards an urban future. Development and improved Quality of Life is possible only with high uptake of energy. Given the level of technology, energy and emission cannot be separated with ease (100% decoupling would be against the Entropy Law), even with the promises made by the green technologies such as solar power, and the overarching operatives of Jevons' paradox and rebound effect. Thus, the source and sink side challenges would become larger in view of ***bigger population and better life styles*** in urban environs. Therefore, minimization of entropy should become a part of the policy paradigm at appropriate levels. Rethinking on urban planning and urban re-engineering is recommended.

3. In the context of NGR's theories "***new processes***" must emerge that have the following characteristics:

(a) Technological innovations: Highly efficient low entropy processes that operate at nearly normal temperature and pressures, and generate almost zero waste, or else chain of such processes which feed on the waste of other processes (but definitely not perpetual motion machines!) .

(b) Life Style changes: The new processes must be driven by new life styles and societal values and choices that are environment friendly, close to nature and promote togetherness, well being and happiness.

4. Mainstreaming of entropy in policy and decision making in the development sector is required. Entropy is a very good measure of resource use and efficiencies of processes, and hence is best suited as instrument of **environmental levies and taxation**. The following interventions are required for mainstreaming of entropy:-

(a) It is important to create research wing that would conduct research on entropy centric strategies and improve entropy study methodologies. This research group could provide the necessary inputs based on ground realities and international best practices which policy makers could incorporate in the regulatory and implementation frameworks, also by making the entropy computation for various process standardized and in easy to comprehend ways.

(b) Standard entropy values and efficiency values of energy transformation should be made available for various processes.

(c) Most policies relating to sustainable development & climate change are framed at national level, and decision making happens at national level. This needs to be also brought at city level. Inventories of climate change protocols are also at global/ national levels, making it difficult to incorporate climate change related action plans based on metrics at local levels. Sectoral regulations and policies need to be revisited to incorporate entropy perspective as stated above.

6.3 Achievements and Significance of the Research:

One of the main achievements of this study is that it has taken forward the theory of NGR on “the Entropy Law and Economic Process” relationship a step ahead by applying his theoretical framework onto the development process and helping in understanding sustainable development from an entropic perspective. The time when NGR wrote the Magnum opus in 1971, it was economic growth that occupied the centre stage and economies were mostly concerned in increasing their GDP by harnessing more and more of natural resources and taking the help of the rapid technological advancement of that era. Today economies have gone through a transition and the focus now is on development, improvement in quality of life and well being. Thus this research assumes its important and enriches the existing transdiciplinary research in the area of ecological economics. This is the first research study of Guwahati city from entropy perspective. Few city studies are based on real time calculations of entropy generation & climate change. This is a unique study which combines waste heat and CO_2 emission together into one using entropy, making a single entropic indicator of climate change which could directly correlate with global warming. The framework developed for conducting the city case study adopts a simple approach and can be taken up for similar such studies of urbanisation from the entropy perspective elsewhere. The scope of the study also can be broadened by taking larger number of economic processes and associated physical, chemical and biological elementary process running within them. Dissemination of research findings among stakeholders would help in creating awareness and mainstreaming the concept and importance of entropy in daily life.

6.4 Limitations

The following are the limitations of the research study:-

1. Lack of literature on thermodynamic entropy studies and application to real world case studies, as well as lack of entropy information about several elementary economic physical and chemical processes.

2. The concept of entropy is not very well understood by many including researchers, policy makers and development functionaries. While conducting the study, it was difficult to explain the purpose of the study and enter into concrete discussions. Entropy is largely understood in public as disorder, and entropy and economics connect is understood with difficulty (while the *Full World-Empty World* concept has easy acceptability!)

3. Lack of consistent data at city level led to difficulties in analysis and drawing conclusions

4. Limited methodological and analytical tools to address interdisciplinary studies impose limits on conducting in-depth analysis.

6.5 Further Research

The study points out at the immense scope of further research in understanding entropy, development and sustainable development relationships. The following recommendations are made in respect of future research in this area:-

1. Studies on extending the Entropy Law and Economic Process theory of NGR need to be carried out further in understanding development process, sustainable development and Climate change. New frameworks, models and metrics are needed to be researched upon.

2. Understanding entropic nature of biological process and their relevance to economic processes and climate change need to be studied in detail.

3. Entropy production due to anthropogenic causes is yet to be mainstreamed opening up a new area for research in sustainability science and climate change debate.

4. There are very few real world studies of entropy and urbanization, as well as entropy and development process. More case studies of finite world systems such as cities need to be taken up to come at better understanding of the relationship.

5. Study on Reemergence of NGR's theories is another area of research which has tremendous scope.

6. The analytical framework suggested in this study is fundamental in nature, and would require further research and testing based on real world economic and development processes. The framework proposed in the study can be tested further by applying fund flow and stock flow concepts laid down by NGR (1971) and arriving at an entropy based production function. One of the main contributions of the study is that it furthers the work of NGR (1971) by moving forward from economic process to development process and sustainable development

APPENDICES

APPENDIX-1A : Applying Systems Approach to Processes

1. Introduction:

In this Appendix, an attempt has been made to comprehend the underlying principles governing a thermodynamic system such as variables defining the system, intensive and extensive variables, state and path functions, thermodynamic equilibrium, concept of generalized work and other key concepts that go into making a system thermodynamic in nature. These concepts are applicable to any thermodynamic system, and are largely the essential properties or characteristics by which one can describe such systems and aid in better understanding of the study hand. With this in mind, two appendices (1A & IB) with elaborate background material on the subject at hand have been prepared and appended to the Thesis to serve as a reference material.

2. Difference Between Newtonian and Thermodynamic Systems:

Before, proceeding further, it is also important to understand the fundamental differences between a thermodynamic system and a classical Newtonian system. There have been fresh attempts to remove mysteries surrounding entropy. Leff (2012) says, "An inability to answer this question can make thermodynamics seem confusing. Classical mechanics deals with point particles and rigid bodies. Both of these are fictitious model systems that do not exist in nature, and are not thermodynamic systems. A point particle can neither rotate nor vibrate and thus cannot store energy within it. This differs from a real atom, which stores energy internally—energy that can vary by absorption and/or emission of radiation. A rigid body's atoms are assumed to be point-like, with fixed positions relative to one another, so energy cannot be added to or taken from such a model system. The simplicity of a rigid body makes it useful for approximating the behavior of real physical systems in classical mechanics, when changes in internal energy are negligible. In contrast, thermodynamics deals with systems that have internal degrees of freedom. For example, the molecules of a gas have kinetic energies and interact with one another via mutual potential energies.” According to Leff, a hypothetical rigid body has zero internal energy (U=0), while an ideal gas system has an internal energy U>0; and the same is variable subject to changes in its pressure, temperature and volume. He further says, “In a macroscopic system the number of individual kinetic and potential energy terms is enormous and impossible to deal with individually. The many molecules of solids typically vibrate about localized lattice sites and have numerous translational, rotational, and vibrational energy modes. Similarly the prodigious number of molecules in a gas have kinetic and intermolecular potential energies. Recognizing the impossibility of dealing with these systems microscopically, the macroscopic internal energy function U is postulated in thermodynamics”. Therefore, according to Leff, the existence of internal energy that can be varied makes a system “thermodynamic”. Therefore, in keeping with the thought process of Leff, the system that we may define for an economic process also must have this property of internal energy U>0.

3. System and Surrounding Relationships:

When a thermodynamic system exchanges energy and matter with the surroundings, it is termed as open system. When the system exchanges only energy from the surroundings, it is termed closed system. When neither energy nor matter is exchanged between the system and surroundings, the system is said to be isolated. An isolated system is ideally the entire universe. Most natural systems such as atmosphere, oceans, biosphere and ecosystems are open systems exchanging matter and energy with surroundings. Open systems are sustained by a continuous supply and removal of matter and energy. These systems may attain steady state conditions in which the properties of the system are invariant when averaged over a given time period. However, the instantaneous values of the open system may undergo oscillations due to existence of net fluxes of mass and energy across the boundaries. Open systems can be classified into three categories namely decaying, cyclic and fluctuating. Decaying or dissipative systems consume their own mass or energy or both. An example would be river runoff during dry season. Cyclic systems follow regular oscillatory behaviour. Gulf stream could be an example of a cyclic system. Randomly fluctuating systems change in an irregular way with unpredictable variations in the variables. An example could be a turbulent whirlwind in the atmosphere. Open systems could also be cascading in nature. A cascading system is a chain of open sub systems which are dynamically linked by a cascade of matter and energy so that output of mass or energy from one sub-system becomes the input for the next subsystem (Peixoto & Oort, 1992, p11). The output of matter and energy from a system may get recycled partially (not fully because, then it would become a perpetual motion machine and violate the laws of thermodynamics) back into the system as input matter or energy. This is called feedback. The feedback is positive when the input acts in the direction of amplifying the output, and negative when the output is dampened. The feedback could occur among the subsystems of a system. A system may have several feedback mechanisms. These could act in series (cascading) or in parallel. Feedback is important in a complex thermodynamic system such as the atmosphere (Peixoto & Oort, 1992, p26-30). Through the boundary conditions, the surroundings may influence the behaviour of the system leading to a forced adjustment of the system variables. This is called external forcing (Peixoto & Oort, 1992, p12). The concept of external forcing is very much used in atmospheric system, especially from the context of climate change.

4. Thermodynamic Equilibrium:

The concept of equilibrium is another key concept. A thermodynamic system needs to be in Mechanical equilibrium, Chemical equilibrium and Thermal equilibrium, then alone we can call the system to be in a state of thermodynamic equilibrium (Zemansky & Dittman, 2011). Further, mechanical equilibrium is one when there is no force or torque in the interior of a system and also none between the system and its surrounding. When a system in mechanical equilibrium does not tend to undergo a spontaneous change internal structure, such as a chemical reaction, or a transfer of matter from any one part of the system to another, however slow, then it is said to be in a state of chemical equilibrium. A system, which is in mechanical and chemical equilibrium, is said to be in thermal equilibrium if there is no exchange of heat between the system and surrounding. In thermal equilibrium, all parts of the system are at the same temperature, and this temperature is same as that of the surrounding. With this definitions in place, one cannot design a system with the sun [at ~5760 K] and earth [at ~298 K] together, and say that they are in thermodynamic equilibrium.

5. Non-Equilibrium State:

When a thermodynamic system does not satisfy any one of the equilibrium types (mechanical, chemical and thermal), the system is said to be in Non-equilibrium state.

6. Work:

Close to the concept of thermodynamic equilibrium is the concept of work. Work is largely understood in terms of Newton's Second Law of Motion. Borrowing standard text book definition of work, “If a system undergoes a displacement under the action of a force, work is said to be done, the amount of work being equal to the product of the force and the component of the displacement parallel to the force (Zemansky & Dittman, 2011). Work done on one part of a system by another part is called internal work and is not discussed in macroscopic thermodynamics (Zemansky & Dittman, 2011). If a system as a whole exerts force on the surrounding or vice versa, and a displacement takes place, the work that is done either by the system or on the system is called external work. External work alone is recognized in thermodynamics. When work is done on a system, work is regarded as positive. Conversely, when work is done by the system, the work is regarded as negative (Zemansky & Dittman, 2011). A thermodynamic system, essentially is characterized to be capable of doing external work. In general terms, the system is said to do W amount of work when it transfers Q_H amount of heat from a hot reservoir at temperature T_H and releases Q_C amount of heat to a cold reservoir at temperature T_C ($< T_H$) as shown in the diagram below:-

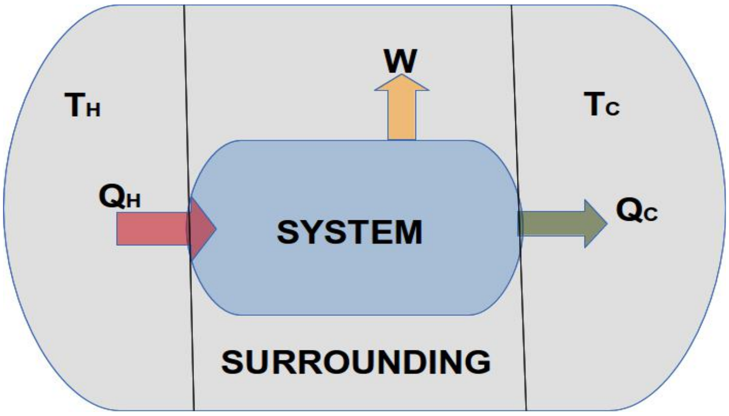

Fig No. A1: A Schematic of a Thermodynamic System (by the Author)

7. System Variables and Equations of State:

A thermodynamic system which is in thermodynamic equilibrium with its surrounding can be described in terms of a set of macroscopic coordinates that do not involve time, called thermodynamic coordinates (Zemansky & Dittman, 2011 p 29). We may also call them system variables. In case of hydrostatic systems such as an ideal gas, Temperature, Pressure and Volume (T, P, V) are the system variables that completely define the system state. The thermodynamic coordinates can be mathematically related with one another by a set of equations of state that define the system in the state of equilibrium. For example, in case of hydrostatic system such as the ideal gas, if any two variables are known, such the third one can be found from the equation of state. For an ideal gas, the equation of state is:

$$PV=nRT \qquad (1)$$

where P is pressure, V volume, T temperature, n is the number of moles of gas and R is the Universal Gas Constant. A generic thermodynamic system may actually have n coordinates. A thermodynamic system can have more than one Equation(s) of State. If a thermodynamic system is described by n variables and m equations of state (n>m), then only n-m variables are independent. An equation of state cannot be deduced from thermodynamic principles alone. Its determination requires either experimental formulation or some other theory such as molecular theory.

8. Intensive and Extensive Variables:

The thermodynamic coordinates could be a mix of intensive and extensive quantities. Intensive quantities such as temperature and pressure do not depend upon the quantity of matter. Whereas quantities such as volume, mass, moles, heat are extensive in nature ie they depend upon the quantity of matter. Dividing one extensive quantity by another, one can obtain intensive quantities such as density (mass/ volume). Entropy is also an extensive quantity (in units of JK^{-1}), but when divided by mass, it becomes an intensive quantity (in units of J $Mole^{-1}$ K^{-1}). *For system to be thermodynamic in nature it should have at least one extensive and one intensive quantity.*

9. State and Path Functions:

Thermodynamic systems are also described by certain functions (in terms of the variables) such as Internal Energy U, Entropy S, Enthalpy H, Gibbs Free Energy G, Helmholtz Energy A etc. It is also pertinent to note that some of thee thermodynamic quantities are state function while others are path functions. State functions are those that do not depend on the manner in which the state was reached (i.e. the path). Irrespective of the path, the value of the state function would be the same under any given condition of the system variables, without depending upon the manner in which those values were arrived at. Path functions on the other hand depend upon the manner in which the change was effected. If for going from point A to B, two different paths are followed, the work done would differ, but the change in entropy would be the same in both the cases. Examples of path functions are heat and work, while entropy is an example of state function. This is a very significant factor in respect of entropy, as whatever path one follows, one is bound to reach the final state of entropy. Its just a question of time (the rate of energy/ resource use).

10. Simple Thermodynamic Systems and Variables:

Some of the simple thermodynamic systems are (Zemansky & Dittman, 2011 p 62):

1. Hydrostatic system: P, V, T
2. Stretched 1-Dimensional Wire: f (Tension), L (Length), T
3. Surfaces and Thin Films: γ (Surface Tension), A (Area), T
4. Electrochemical Cell: ε (EMF), Z (Charge), T
5. Dielectric Solid: E (Electrical Field), *P* (Polarization), T
6. Paramagnetic Solid: H (Magnetic Field), M (magnetization), T

11. Adiabatic and Isothermal Processes:

An adiabatic process is said to take place when work is done either by the system on the surrounding or vice versa without transfer of any heat between the system and its surrounding. This can occur when the system is thermally isolated from the surroundings so that no exchange of heat takes place during the process, or the process happens in such a short time that exchange of heat is negligible. In adiabatic process, when the surrounding does work on the system, the internal energy of the system increases, and when the system does work on the surroundings, its internal energy decreases. Adiabatic heating occurs when, say in a hydrostatic system, the fluid is compressed by the surroundings. Adiabatic cooling occurs when, say in a hydrostatic system, the fluid expands due to reduced pressure in the surroundings. On the other hand, an isothermal process is one, in which during the transformation, there is no change in the temperature of the system. In order for this to happen, the system must be in constant touch with the surrounding (or a thermal reservoir), and the change must take place slowly enough so that the system can maintain the original temperature by exchanging heat with the surrounding. When the surrounding does work on the system, the temperature of the system rises, and the temperature is maintained by ejecting certain amount of heat to the surrounding. Similarly when the system is doing work on the surrounding, the temperature of the system falls, but certain amount of heat flows from the surrounding to the system to maintain the temperature.

12. Reversible and Irreversible Processes/ Changes:

A reversible change in thermodynamics is one in which the change can be reversed by an infinitesimal modification of a variable or coordinate. The direction of change can be reversed in a such a process. If a system and its surrounding are in thermal equilibrium, a small change in temperature of one will induce exchange of heat and bring back the system variables to the original value. Reversibility and equilibrium are closely related. Systems at equilibrium are poised to undergo reversible change (Atkins & de Paula, 2010 p 51). Such a process may take infinite time to change from one state to another. To the contrary, an irreversible change would happen in a finite time, proceed in one direction and cannot be traced back to its original state by infinitesimal changes in variables. Burning of fuel is an example of an irreversible process.

13. Bulk Matter

Bulk matter consists of large quantities of atoms, molecules or ions, and can have its physical state as solid, liquid and gas. The state of a sample of bulk matter is defined by specifying its properties such as mass, amount, volume, pressure and temperature. The amount of substance, n, (known as number of moles), is a measure of the number of specified entities present in the sample, per mole having Avogadro Number – 6.022×10^{23} (Atkins & de Paula, 2010 p 5).

14. Sensible and Latent Heat:

The heat that is used up to increase temperature of a body or system is called sensible heat. The heat that is used up to change the state of matter (without changing of temperature) is called latent heat.

15. Energy:

Energy is the capacity to do work. The total energy of a particle is the sum of its kinetic and potential energies. Energy is conserved, neither it can be created nor destroyed, but only can be transferred from one location to another and transformed from one form to another. (Atkins & de Paula, 2010 p 6-7)

16. Internal Energy:

The total energy of a system is called its internal energy U, which is the sum total of all the kinetic and potential energies of the molecules in the system. The internal energy is a state function. The First law of Thermodynamics states that internal energy of an isolated system is constant. The internal energy is an extensive property. (Atkins & de Paula, 2010 p 47)

APPENDIX-1B : Laws Of Thermodynamics

1. Introduction:

This Appendix explores the 2 most important laws of Thermodynamics and the associated concepts and application of the laws. The Zeroth Law and the Third Law of Thermodynamics have been deliberately omitted.

2. The First Law of Thermodynamics:

In thermodynamics the total energy of a system is called its Internal Energy. The internal energy is the total kinetic and potential energy of the molecules in the system. The change in internal energy is denoted by ΔU when a system changes from an initial state i with internal energy U_i to a final state f of internal energy U_f

$$\Delta U = U_f - U_i \quad (1)$$

The internal energy is a state function in the sense that its value depends only upon the current state of the system and is independent of how that state has been prepared. In other words it is a function of the properties that determine the current state of the system. Changing any one of the state variables, such as pressure, results in a change in the internal energy. The internal energy is an extensive property. An extensive property is a property that depends on the amount of substance in the sample. Examples are mass and volume. Intensive property is a property that is independent of the amount of substance in the sample. Examples are temperature, pressure and density. Internal energy of system may be changed either by doing work on the system or by heating it. Both heat and work are equivalent ways of changing the system's internal energy. These two are examples of path functions. Having dwelt with some of the basic terms, the First law of thermodynamics is expressed as follows:

The internal energy of an isolated system is constant or that energy cannot be created and cannot be destroyed. The mathematical statement of the First law is given by:

$$\Delta U = Q + W \qquad (2)$$

where Q is the amount of energy transferred as heat to a system and W is the work done on the system. The equation above summarizes the equivalence of heat and work and the fact that internal energy is constant in an isolated system.

3. The Second Law of Thermodynamics:

The Second Law of Thermodynamics states that **the entropy of an isolated system always increases**. The Clausius Statement of the second law of thermodynamics is: "*Heat never flows spontaneously from a colder body to a hotter body*". The statement of the second law formulated by Kelvin is as follows: "No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work". Entropy is a state function and is an extensive property. *The first law uses internal energy to identify permissible changes; the second law uses the entropy to identify the spontaneous changes among those permissible changes*. The thermodynamic definition of entropy is based on the equation

$$\Delta S = \frac{dQ_{rev}}{T} \qquad (3)$$

For a measurable change between two states i and f this equation integrates to

$$\Delta S = \int_i^f \frac{dQ_{rev}}{T} \qquad (4)$$

To calculate between any two states of a system, we find a reversible path between them, and integrate the energy supplied as heat at each stage of the path divided by the temperature at which heating occurs. (Atkins, 2006). When two systems of different temperatures are in thermal contact, heat flows out of the hotter system and into the colder system. There is no change in the total energy of the two systems; energy just flows out of one into the other. Why then does heat flow in one direction but not in the other? It is seen that heat flow into a system not only increases the system's internal energy, it also increases the disorder of the system. Heat flow out of a system decreases not only its internal energy, but also its disorder. The entropy of a system (S) is a quantitative measure of the dissipation of energy. The word entropy was coined by Rudolf Clausius in 1865. Its Greek root means evolution or transformation. The SI unit of entropy is JK^{-1}. Heat flowing into a system increases the system's entropy (both ΔS and Q are +ve); whereas heat leaving a system decreases the system's entropy (both ΔS and Q are -ve). If an amount of heat Q flows into a system at constant absolute temperature T, the entropy change of the system is

$$\Delta S = \frac{Q}{T} \tag{5}$$

The above equation is valid as long as the temperature of the system is constant, which is true if the heat capacity of the system is large (as for a reservoir), so that the heat flow Q causes a negligible small change in temperature of the system. The equation only gives a change in the entropy, and not the initial or final values. If a small amount of heat Q flows from a hotter system to a colder system ($T_H > T_C$) . The total entropy change of the system is

$$\Delta S_{TOT} = \Delta S_H + \Delta S_C = -\frac{Q}{T_H} + \frac{Q}{T_C} \tag{6}$$

Since $T_H > T_C$

$$\frac{Q}{T_H} < \frac{Q}{T_C} \tag{7}$$

The increase in the colder system's entropy is larger than the decrease of the hotter system's entropy, and the total entropy increases.

$$\Delta S_{TOT} > 0 \tag{8}$$

Thus, the flow of heat from a hotter system to a colder system causes an increase in the total entropy of the two systems. Every irreversible process increases the total entropy of the universe. **A process that would decrease the total entropy of the universe is impossible**. A reversible process causes no change in the total entropy of the universe. The second law can be restated in terms of entropy that "*the entropy of the universe never decreases*". The second law of thermodynamics determines what we sense as the direction of time. Entropy is not a conserved quantity like energy. The entropy of the universe is always increasing. It is possible to decrease the entropy of a system, but only at the expense of increasing the entropy of the surroundings by atleast as much (usually more). [Giambattista, 2008].

4. History of Thermodynamics:

The very low efficiencies of the Savery Engine developed prior to 1698, followed by the Newcomen Engine, and later the Watt Engine, about 2% of the input could only be converted to useful work, promted the thinkers of those days to look for a new science of engine dynamics, and thus, thermodynamics was born. Sadi Carnot's 1824 paper *Reflections on the Motive Power of Fire* is often seen as the starting point for thermodynamics as a modern science. Carnot is credited with the first modern day definition of "work": *weight lifted through a height*. In 1845, Joule laid the foundations of conservation of energy through his best-known experiment, involving the use of a falling weight to spin a paddle-wheel in a barrel of water, which allowed him to estimate a mechanical equivalent of heat of 819 ft·lbf/Btu (4.41 J/cal). The name "thermodynamics," however, was coined by the British mathematician and physicist William Thomson (Lord Kelvin) in 1849 in a paper on the efficiency of steam engines. In 1850, the famed mathematical physicist Rudolf Clausius defined the term entropy S to be the heat lost or turned into waste, stemming from the Greek word "entrepein" meaning to turn. Clausius presented the first-ever mathematical formulation of entropy, although at this point in the development of his theories he called it "equivalence-value", perhaps referring to the concept of the mechanical equivalent of heat which was developing at the time rather than entropy.

In 1865, Clausius gave irreversible heat loss, or what he had previously been calling "equivalence-value", a name: “*I propose to name the quantity S the entropy of the system, after the Greek word [τροπη trope], the transformation. I have deliberately chosen the word entropy to be as similar as possible to the word energy: the two quantities to be named by these words are so closely related in physical significance that a certain similarity in their names appears to be appropriate*”. Although Clausius did not specify why he chose the symbol "S" to represent entropy, it is argued that Clausius chose "S" in honor of Sadi Carnot. On the first page of his original 1850 article "On the Motive Power of Heat, and on the Laws which can be Deduced from it for the Theory of Heat", Clausius calls Carnot the most important of the researchers in the theory of heat (wiki). The advent of thermodynamic theories led to a new school of thought which departed from the classical Newtonian mechanics. Thermodynamic processes, in nature, are irreversible and therefore, dependent with respect to time. However, mechanical processes are reversible and hence time independent (Mirowski, 1984).

5. Gibb's Free Energy and Entropy:

For systems and processes on the earth which take place at constant temperature and pressure, there is another state function called Gibb's Free energy becomes relevant.

$$\Delta G = \Delta H - T\Delta S \qquad (9)$$

Albert Lehninger argues that the order produced within cells as they grow and divide is more than compensated by the disorder they create in their surroundings in course of their growth and division. The living organisms preserve their internal order by taking from their surroundings free energy in form of nutrients or sunlight and returning to their surroundings an equal amount of energy as heat and entropy.

6. Statistical Interpretation of Entropy:

Thermodynamic systems are collections of huge number of atoms and molecules. These atoms or molecules statistically determines the disorder of the system. In other words, the second law of thermodynamics, is based on the statistics of systems with extremely large large number of atoms or molecules (Giambattista, 2008). In classical thermodynamics, we deal with single extensive systems, while in statistical mechanics we recognize the role of the tiny constituents of the system. The temperature, for instance, of a system defines a *macrostate*, whereas the kinetic energy of each molecule in the system defines a *microstate*. The macrostate variable, temperature, is recognized as an expression of the average of the microstate variables, an average kinetic energy for the system. Hence, if the molecules of a gas move faster, they have more kinetic energy, and the temperature naturally goes up. The molecular interpretation of the second law of thermodynamics is a realization that an atom or molecule can possess only certain energies called its energy levels. Although we cannot keep track of the energy state of a single molecule, we can speak of the population of the state, the average number of molecules in each state; these populations are constant in time provided the temperature remains the same. The lowest energy state is occupied at T=0. Raising the temperature excites some molecules into higher energy states, and more and states become accessible as the temperature is raised further. Nevertheless, whatever the temperature, there is always a higher population in a state of low energy than one of high energy. Ludwig Boltzmann made the link between the distribution of molecules over energy levels and the entropy. According to him, the entropy of a system is given by

$$S = k \ln W \tag{10}$$

where W is the number of microstates, the ways in which the molecules of a system can be arranged while keeping the total energy constant. The concept of number of microstates makes quantitative the ill defined qualitative concepts of disorder, and the dispersal of matter and energy that are used widely to introduce the concept of entropy: a more disorderly distribution of energy and matter corresponds to a greater number of microstates associated with the same total energy. The letter “k” in the equation 10 is the Boltzmann's Constant having a value 1.381 X 10^{-23} JK^{-1}.

7. Entropy and Information Theory:

In Shannon information theory, the entropy is a measure of the uncertainty over the true content of a message, but the task is complicated by the fact that successive bits in a string are not random, and therefore not mutually independent, in a real message. Also "information" is not a subjective quantity here, but rather an objective quantity, measured in bits. Shannon, in his paper “A mathematical Theory of communication” (1948) introduced an H function of the following form:

$$H = -K \sum_{i=1}^{k} p(i) \log p(i) \tag{11}$$

where K is +ve constant. Information entropy is present whenever there are unknown quantities that can be described only by a probability distribution, and is a much more generalized concept than statistical thermodynamic entropy.

8. Entropy and Biotic & Abiotic Processes

This section deals with relationship between entropy production in biotic and abiotic systems. The concept of negentropy has been introduced in this section. "Nothing is easier than to admit in words the truth of the universal *Struggle for Life*, or more difficult—at least I have found it so—than constantly to bear this conclusion in mind. Yet unless it be thoroughly engrained in the mind, I am convinced that the whole economy of nature, with every fact on distribution, rarity, abundance, extinction, and variation, will be dimly seen or quite misunderstood. We behold the face of nature bright with gladness, we often see superabundance of food; we do not see, or we forget, that the birds which are idly singing round us mostly live on insects or seeds, and are thus constantly destroying life; or we forget how largely these songsters, or their eggs, or their nestlings, are destroyed by birds and beasts of prey; we do not always bear in mind, that though food may be now superabundant, it is not so at all seasons of each recurring year". **—Charles Darwin**, *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*, (Darwin, 1876).

9. Reversibility, Irreversibility and the Arrow of Time:

Prigogine showed that Self-Organization appears in Nature far from equilibrium and that Irreversibility and Probability are intrinsic properties of Nature at all levels, from atoms and nuclei to our everyday life up to the cosmological scale. His work is a continuation of the dialogue about Time and Change in Nature, initiated by Heraclitus and Parmenides and continued by Zeno, Epicurus, Lucretius, Kant, Hegel, Einstein and other eminent thinkers over the centuries.

10. Entropy In Living (Negentropy) and Non Living Systems:

All living things attempt to modify their environment for their own needs, by creating what for them is order. In 1943 Erwin Schrödinger, Nobel Laureate in Physics, used the concept of "negative entropy" in his popular-science book "What is life?" Life feeds on negative entropy! The creation of order is one definition of negative entropy. One of the definitions of life might be the ability of a life form to create order. Inanimate objects do not possess this property. In 1982, American biochemist Albert Lehninger argued that the "order" produced within cells as they grow and divide is more than compensated for by the "disorder" they create in their surroundings in the course of growth and division. "Living organisms preserve their internal order by taking from their surroundings free energy, in the form of nutrients or sunlight, and returning to their surroundings an equal amount of energy as heat and entropy." Entropy and negentropy can be transferred from one sub system to another. The entropy law does not prevent the accumulation of low entropy or negentropy in one subsystem at the expense of increasing entropy in another. (Ayres, 1998).

11. Evolution of Life and The Second Law:

Some have argued that evolution cannot have occurred because it would violate the second law of thermodynamics. The argument views evolution as an increase in order: life spontaneously developed from simple life forms to more complex, more highly ordered organisms. However, the second law says that the total entropy of the universe cannot decrease. It does not say that the entropy of a particular system cannot decrease. When heat flows from a hot body to a cold body, the entropy of the hot body decreases, but the increase of the cold body's entropy is greater. So the entropy of the universe increases. A living organism is not a closed system. An adult human, for instance, requires roughly 10 MJ of chemical energy from food per day. Some of this energy is turned into useful work by the muscles, some more is used to repair body tissues, but most of it is dissipated and leaves the body as heat. The human body, therefore, is constantly increasing the entropy of its environment. As evolution progresses from simpler to more complicated organisms, the increase in order within the organism must be accompanied by a larger increase in disorder in the environment (Giambattista, 2008). “Energy is needed to replace not only the mechanical energy of our bodily exertions, but also the heat we continually give off to the environment. And that we give off heat is not accidental, but essential. For this is precisely the manner in which we dispose of the surplus entropy we continually produce in our physical life process. This seems to suggest that the higher temperature of the warm-blooded animal includes the advantage of enabling it to get rid of its entropy at a quicker rate, so that it can afford a more intense life process. I am not sure how much truth there is in this argument (for which I am responsible, not Simon). One may hold against it, that on the other hand many warm-blooders are protected against the rapid loss of heat by coats of fur or feathers. So the parallelism between body temperature and 'intensity of life', which I believe to exist, may have to be accounted for more directly by van't Hoff’s Law,: the higher temperature itself speeds up the chemical reactions involved in living. (That it actually does, has been confirmed experimentally in species which take the temperature of the surroundings.)”. [Schrodinger, 1944]. As shown by R. U. Ayres [1998, 2004], the rate of entropy production by a living organism can be understood as a measure of its organic complexity. Biological evolution tends towards increasing internal order of the organism. The evolutionary process is primarily driven by consumption of low entropy energy from the sun. A living organism, thus, can be regarded as an entropy generator. However, the main (and crucial) difference between biological and economic perspectives on evolution can be summarized succinctly. Biological evolution is a very slow unconscious process driven by physical phenomena (e.g., mutation) and implemented by competitive reproductive strategies adapted to specific environmental ‘niches’. Economic evolution is, of course, much faster than biological evolution. Moreover, it is entirely driven by conscious human decisions bearing little resemblance to mutation and adjustment via population dynamics. A crucial condition of an industrial economy operating through time is its ability to obtain flows of low entropy energy and materials. As Alfred Lotka noted, any organism that discovers how to take advantage of unused energy running over a dam gains a selective advantage over other organisms [Christensen, 1991]. The essential ecological difference between people and other species is that, in addition to our biological metabolism, people created enterprises with industrial metabolism. This stands as a crucial opposition to evolution of biosphere, which took many billions of years to evolve. Thus, the society, trying to achieve "economic evolution", should "take lessons" from the biosphere [Čiegis, 2004]. Lovelock [1979] who proposed the **Gaia concept** of the earth was asked to study the prospects of life on mars. He is best known for proposing the Gaia hypothesis, which postulates that the biosphere is a self-regulating entity with the capacity to keep our planet healthy by controlling the chemical and physical environment. Lovelock invented the electron capture detector, which ultimately assisted in discoveries about the persistence of CFCs and their role in stratospheric ozone depletion. In 1964, James Lovelock was among a group of scientists who were requested by NASA to make a theoretical life detection system to look for life on Mars during the upcoming space mission. When thinking about this problem, Lovelock wondered "how can we be sure that Martian life, if any, will reveal itself to tests based on Earth's lifestyle?" To Lovelock, the basic question was "What is life, and how should it be recognized?" When speaking about this issue with some of his colleagues at the Jet Propulsion Laboratory, he was asked what he would do to look for life on Mars. To this, Lovelock replied, "I'd look for an entropy reduction, since this must be a general characteristic of life." Thus, according to Lovelock, to find signs of life, one must look for a "reduction or a reversal of entropy.

12. Entropy Exportability, Entropy Balance, Entropy Analysis and Efficiency:

The entropy exportability of the planet is mainly determined by the temperature of the upper atmosphere. Energy conservation dictates that this temperature is more or less fixed, setting a natural limit for Earth's entropy export. On the other hand, one of the necessary conditions for a preservation of the (dynamical) status quo of life on Earth is a constant entropy content of the Earth. In other words: all living organisms on Earth can only produce entropy at a certain rate so that the total rate does not exceed the natural limit given by the entropy exportability of the Earth. If one species increases its entropy production rate, other species have to decrease theirs in return so that the net result is balanced. Again, knowing the actual entropy production of the human population would allow to quantify its role in the dissipative system of the Earth and eventually give rise to establishing real 'limits to growth'. Having calculated the entropy production associated with a process (or the human population), this should be compared to a common standard or an intrinsic quantity of the process. This is very much related to finding a measure for the efficiency of the process. The meaning of this is obvious when one considers entropy production as a measure for resource use. If two competitive processes with differing entropy production are considered the one with the lower value is the more efficient one (in this 'entropical' sense), since it uses (i.e. transforms) less resources. For processes that have the same product or function, the entropy production (per product unit) works fine as a measure of efficiency (GoẄling 2001)

13. Efficiency

In thermodynamics, two efficiencies in general are recognised each pertaining to the two laws of the Thermodynamics, namely the First Law and the Second Law. Efficiency of conversion is given by

$$\eta = \frac{E_{output}}{E_{input}} = \frac{P_{output}}{P_{input}} \tag{12}$$

where E_{input} is input energy and E_{output} is useful energy outputted by the conversion process. E*nergy conversion goes against nature and nature imposes a 'tax' on it.* Part of the energy input is wasted. It is used to increase the entropy of the surroundings. In case there are n number of processes involved in conversion of one form of energy into another, with each process having a conversion efficiency i, the overall efficiency of conversion is given by the formula:

$$\eta = \prod_{i}^{n} \eta_i \tag{13}$$

13.1 The First Law Efficiency: The First law of Thermodynamics talks of conservation of energy and conversion of energy from one form into another. One can measure the efficiency of the conversion process from one form of energy to another by "Energy Efficiency". According to Skogestad (2009), The first law efficiency can be defined as "the fraction of useful energy in that is converted into useful energy out":

$$\eta_{energy} = \frac{(useful)\, energyout}{(useful)\, energy\, \mathrm{in}} \tag{14}$$

The First Law Efficiency is a conversion efficiency between two energy forms. This also distinguishes between energy form that are useful and energy forms that cannot be utilized. For example friction causes energy losses, as the heat developed due to friction is scattered and cannot be easily utilized. If the loss, i.e. the heat lost to the surroundings or the cooling air or water etc. (say Qc) is made use of economically through a feedback process, the efficiency would be defined as:

$$\eta_{energy} = \frac{W_{cycle} + Q_C}{Q_H} \tag{15}$$

The First Law efficiency is also referred to as thermal efficiency, and is is used for book-keeping to detect possible heat losses from the process. The First Law efficiency does not indicate the performance of the process in comparison to an ideal process or a reversible process (Gundersen T, 2011).

13.2 The Second Law Efficiency: According to Skogestad (2009), the Second Law efficiency, also called Thermodynamic efficiency can be defined in two ways for processes where we remove energy or supply energy. For processes where we take out useful energy, efficiency can be be defined as:

$$\eta = \frac{actual\_useful\_energy\_out}{ideal(maximum)\,useful\_energy\_out} \qquad (16)$$

For a process where useful energy is put in, the efficiency can be defined as:

$$\eta = \frac{ideal(maximum)\,useful\_energy\ \mathrm{in}}{actual\_useful\_energy\ \mathrm{in}} \qquad (17)$$

13.3 Nature of Efficiency: Efficiency has multiplicative property. In case there are n number of processes involved in conversion of one form of energy into another, with each process having a conversion efficiency i, the overall efficiency of conversion is given by the formula:

$$\eta = \prod_{i}^{n} \eta_i \qquad (18)$$

For example, if a power plant consists of three parts i.e. a boiler (to convert fossil fuel's chemical energy into heat , and used to make steam out of water) with an efficiency of 88%, a turbine (which converts the steam flow into mechanical energy to rotate the magnetic coil) with an efficiency of 40%, and a generator (which converts mechanical energy into electrical energy) with an efficiency of 98%.; the overall efficiency of the power plant is given by

$$\eta = 0.88 \text{ X } 0.40 \text{ X } 0.98 = 0.35 \qquad (19)$$

The rest of the energy is lost as heat to the surroundings, satisfying the second law of thermodynamics.

14. Mechanisms of Entropy Transfer between System and Surrounding

There are three ways entropy could be generated or transferred: heat transfer, mass transfer and entropy generation due to irreversibilities. When Q amount of heat (or ΔE waste heat) is transferred from system to surrounding or vice versa at the boundary at absolute temperature T, the associated entropy change is given by:

$$\Delta S = \frac{Q}{T} = \frac{\Delta E}{T} \qquad (20)$$

If this heat was not rejected by the system, the system could get heated up instead which may not be safe for the system. The excess heat must be removed even by applying special cooling systems. (Cengel & Boles, 2011).

15. Energy and Its Forms

Treatment of energy would become highly exhaustible and may go out of scope as energy is one of the most researched entities in Physics. A basic understanding of energy has been provided in this chapter. Though matter and energy both interact in a thermodynamic system, no separate write up has been given on matter at this stage. A separate study is planned on entropic nature of matter. The matter-energy equivalence itself forms a vast spectrum of studies. However, its application in real world is not straight forward. The energy is manifested in many forms, but largely classified as primary and secondary sources from the availability of energy point of view. All primary energy sources are low entropy in nature and deteriorate to higher entropy secondary energy sources. The present chapter attempts to study energy from primary sources perspective.

Energy is found in several forms, most common among them being Thermal energy (Heat energy), Chemical energy (including energy from food items), Electrical energy, Magnetic energy, Radiation energy (energy of the electromagnetic waves including solar energy and Light energy), Sound energy, Mechanical energy (sum of kinetic and potential energies), Nuclear energy (Fission and Fusion energy). According to classical mechanics, there are two types of energies namely Potential energy (by virtue of position of a body) and Kinetic energy (by virtue of motion of a body). The Potential energy is given by the formula:

$$P = mgh \tag{21}$$

where P is the Potential energy, m is the mass of the body, g is the acceleration due to gravity and h is the height of the body from the surface of the earth.

The Kinetic energy is given by the formula:

$$K = \frac{1}{2} m v^2 \tag{22}$$

where K is the Kinetic energy, m is the mass of the body and v is the velocity of the body.

Energy contained in electromagnetic radiation is given by the formula:

$$E = h \nu \tag{23}$$

where E is the energy contained in a radiation of frequency ν (in Hertz); h is the Plank's constant having the value 6.626068×10^{-34} m^2 Kg s^{-1}.

16. Primary Forms of Energy

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels (coal, petroleum and natural gas, biofuels, nuclear fission and fusion energy), and other forms of energy received as input to a system (solar energy received from the Sun). Primary energy can be non-renewable or renewable. Primary energy is also called "high quality" energy. The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. In 2002, this was more energy in one hour than the world used in one year. Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

Another source of energy arises out of the Albert Einstein's equation of energy and mass equivalence:

$$E = MC^2 \qquad (24)$$

where E is the energy, M is the mass and C is the velocity of light in vacuum (~ $3X10^8$ ms^{-1}). Energy equivalent of 1 gram of mass is equal to 89.9 TJ or 25 GWh of energy supply. However, the conversion processes of mass into energy are highly inefficient. The efficiency of a typical fission process would be about 0.04%, and a fusion process could be about 0.3%. While conversion of mass into energy is a viable option, the conversion of energy into mass still seems to be a very distant dream. By equivalence relationship shown by the $E=MC^2$ equation above, it should take about 89.9 TJ of energy to create 1 gram of mass. However, this has not yet been realized by any one outside the linear particle accelerators, and the one time Big Bang. However, the findings of Kirk McDonald of Princeton University hold some hope.

APPENDIX-2 : Economic Activity Code Details

Code	Description	Code	Description	Code	Description
0112	Growing of rice				
0220	Logging				
4100	Construction of buildings	2394	Manufacture of cement, lime and plaster	0810	*Quarrying of stone, sand and clay*
				0510	*Mining of hard coal*
		2392	Manufacture of clay building materials	0510	*Mining of hard coal*
				0810	*Quarrying of stone, sand and clay*
		2410	Manufacture of basic iron and steel	*0710*	*Mining of iron ore*
				1910	*Manufacture of coke oven products*
				0510	*Mining of hard coal*
4921 4923	Urban and suburban passenger land transport	*1920*	*Manufacture of refined petroleum products*	*0610*	*Extraction of crude petroleum*
4923	Freight transport by road				
9820	Undifferentiated service-producing activities of private households for own use	*1920*	*Manufacture of refined petroleum products*	*0610*	*Extraction of crude petroleum*
		3510	Electric power generation, transmission and distribution	0510	*Mining of hard coal*

APPENDIX-3A : Factors & Formulae Used In Electricity Case Study

A. Factors for CO_2 Emission, Resource Use (Coal) and Entropy Generation

$$E_{CO_2} = \frac{0.8 \bullet E_{HH} \bullet 3600 \bullet \left(\frac{44}{12}\right)}{\eta_{DTR} \bullet \eta \bullet_{GRID} \bullet \eta_{Plant} \bullet 32.792} \quad (1)$$

$$E_{CO_2} = \frac{0.8 \bullet 402.537 \bullet E_{HH}}{\eta_{DTR} \bullet \eta \bullet_{Grid} \bullet \eta_{Plant}}$$

$$M_{Coal} = \frac{0.8 \bullet E_{HH} \bullet 3600}{\eta_{DTR} \bullet \eta \bullet_{Grid} \bullet \eta_{Plant} \bullet 32.792 \bullet 0.3475} \quad (2)$$

$$M_{Coal} = 0.8 \bullet 315.922 \bullet \frac{E_{HH}}{\eta_{DTR} \bullet \eta \bullet_{Grid} \bullet \eta_{Plant}}$$

$$\Delta S = \frac{E_{HH}}{\eta_{Plant} \bullet \eta_{Grid} \bullet \eta_{DTR}} \left(0.8 + 0.2 \bullet \eta_{Plant} - \eta_{Plant} \bullet \eta_{Grid} \bullet \eta_{DTR} \bullet \eta_{HH}\right) \frac{3600}{298} \quad (3)$$

$$\Delta S = 12.0805 \bullet \frac{E_{HH}}{\eta_{Plant} \bullet \eta_{Grid} \bullet \eta_{DTR}} \left(0.8 + [1 - 0.8] \bullet \eta_{Plant} - \eta_{Plant} \bullet \eta_{Grid} \bullet \eta_{DTR} \bullet \eta_{HH}\right) \quad (4)$$

where

E_{HH} = Energy (Electricity) injected or billed at house hold (consumer) level in MU

η_{HH} = Average Efficiency of electrical appliances: light, fan, TV, refrigerator etc.

η_{DTR} = Average Efficiency of distribution network from DTR to Household (HH)

η_{Grid} = Efficiency of the Grid

η_{Plant} = Average Efficiency of the thermal power plants[a]

E_{co2} = Emission of CO_2 in tons (released from burning of coal in the plant)

M_{coal} = Mass of coal in tons required to generate the energy

ΔS = Entropy generation in GJ K^{-1}

0.8 = Fraction of grid power from thermal energy. (=0.80 for Guwahati city[b])

– An indicator of greenness of power, the lesser the greener the power

3600 = No of seconds in 1 hour (used in 1 kWh =3.6 MJ conversion)

44/12 = Ratio of molecular masses of CO_2 and C. Used for C to CO2 conversion

32.792 = Amount of energy released in MJ on burning of 1 Kg of C[c]

0.3475 = Fraction of C content in coal[d]

[a] The efficiency of thermal power plants can also be assessed from the average Station Heat Rate (kcal/kWh). For a 100% efficient plant, 3.6 MJ (=860.421 kcal) energy input is required. A plant having 2607 SHR would be 33% efficient. Average SHR for NTPC plants for 2012-13 was 2399 (η_{Plant} =35.86%) (CEA, 2014). The All India Average SHR for 2006-07 was 2861 (30%) (CEA, 2007). The All India Average Design STR is 2398 (35.88%) (CEA, 2007).

[b]The grid supply for Guwahati, as per utility officials has a mix of 80% thermal and 20% hydel energy components. However, at all India level, it may be noted that as of August, 2015 189.3 GW is the total thermal installed capacity against a total of 272.5 GW installed capacity of all types of power plants in India (IBEF, 2015). Therefore, the thermal component at all india level would be 67% to 70%.

[c]Carbon reacts with oxygen to produce CO_2 and releases 393.50 kJ $Mole^{-1}$(393.512 kJ $Mole^{-1}$) of energy, which is also known as ΔH^0_{298} i.e. Standard Enthalpy of Reaction. Since there are 83.33 moles per kg of carbon, the enthalpy value of the reaction comes to 32792.35 kJ kg^{-1} (32.792 MJ kg^{-1}).

[d]Carbon content of coal varies widely. The value of 0.3475 has been obtained by averaging the quality of coal actually used by 10 power plants in India as reported by Mittal (2012).

B. Efficiency & Wattage Reduction Values used in the What If Scenario Analysis:

SCENARIO PATHWAYS	DESCRIPTION
SC11	**BAU**: η_{HH} = 0.35; η_{DTR} = 0.88135; η_{Plant} = 0.33 & no change in per capita power
SC12	↑ η_{HH} = 0.38; ↑η_{DTR} = 0.94; ↑η_{Plant} = 0.38 (↑Increase efficiencies) & no change in per capita power
SC21	↓ W (↓Reduce consumption by 10 W to 100W per capita) & no change in efficiencies
SC22	↑ η_{HH} = 0.38; ↑η_{DTR} = 0.94; ↑ η_{Plant} = 0.38 (↑Increase efficiencies) & ↓ W (↓Reduce consumption by 10 W to 100 W per capita)

C. Values of CO_2, Resource (Coal) and Entropy Generation per 1U E_{HH} in SC12 Scenario of Increased Efficiencies

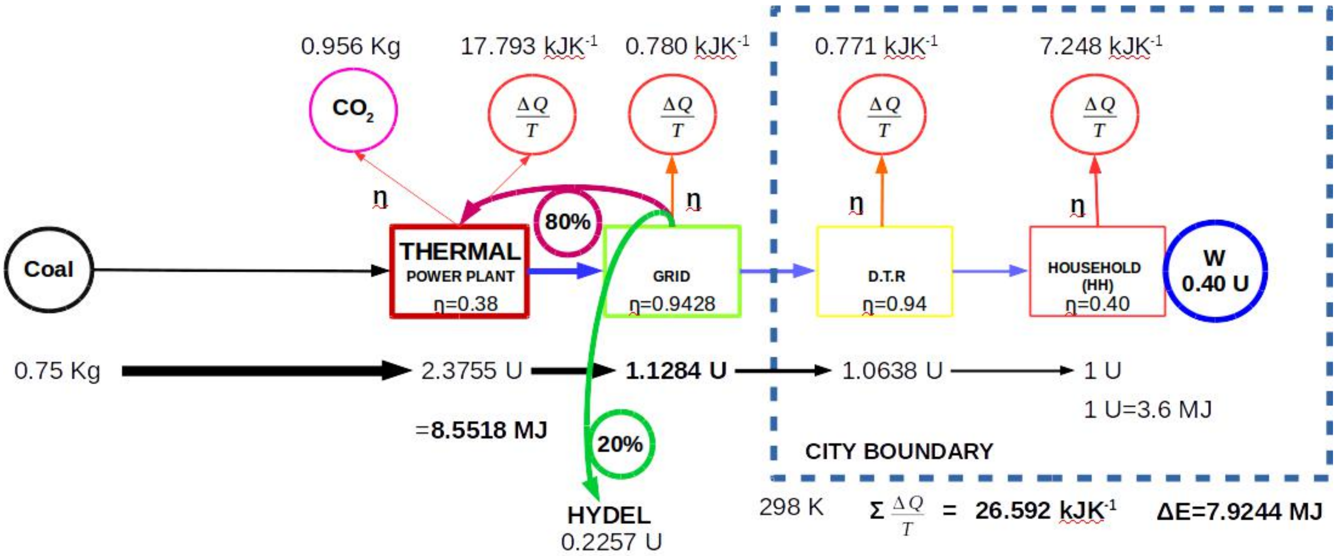

Fig No. A2: Values of CO_2 and Entropy for 1 Unit of Electricity at HH (SC12)

APPENDIX–3B : Factors & Formulae Used in Building Case Study

1. Guwahati City Building Case Study:

The Guwahati city as a unit of development has been examined in some detail from the building construction perspective. Guwahati is one of the fastest growing cities of India. On an average about 1 million square meter of built up space is added annually. Therefore, a study based on quantum of construction, associated energy and mass flow, entropy generation and CO_2 emission of the city was studied. A brief on methodology pertaining to building is given below:

2. Methodology:

The methodology can be broken into three steps for the built up space study:

1. Primary Data collection
2. Secondary Literature Review
3. Model Building
4. Data Analysis

3. Primary Data Collection: The two sources of primary data, in form of Building Permissions, were Guwahati Metropolitan Development Agency (GMDA) and Guwahati Municipal Corporation (GMC). The GMDA dataset was available from 2007 till 2014. It had 36 fields and 14295 rows, which amounts to 514620 number of entries. The biggest challenge was that none of these entries were standardized, and each entry had to be manually handled, corrected and codified for further processing. Thereafter, the data was classified into yearwise floorwise information with floor area as the key parameter. The key fields used were (*F means Floor, 10F means 10th Floor of the building*):

1. Year of Building Permission
2. Floors (Coded as Basement, 0F, MF, 1F,2F…… 10F)
3. Floor Usage (Parking, Residential, Shop, Commercial, Hotel etc.)

4. Floor wise Area (Coded as Basement, 0F, MF, 1F,2F…… 10F)
5. Total area
6. Building type (Assam Type, RCC)

On the other hand, the GMC dataset was from 2014 till 2016. It contained 2949 rows with 7 fields. However, the data lacked floor wise area details. Therefore, floor wise analysis could not be done for the entire dataset. PWD, Assam was approached for providing inputs on per sq meter requirement of construction materials. The inputs given from the PWD is summarized below:

Table No. A3.1: Requirement of Building Materials per m^2

Sl No.	Building Type	Floor	Cement (Kg) (CuM)	Sand (CuM)	Aggregate (CuM)	Steel (Kg)	Brick (Nos)
1	Assam Type	-	125 (0.085)	0.017	0.340	12.50	75
2	RCC	GF	300 (0.204)	0.408	0.816	50	75
3	RCC	Other Floors	200 (0.136)	0.272	0.544	30	75

4. Data from Secondary Sources: Data and information on embodied energy, CO2 emissions, chemical reactions, hydration and curing processes etc. was collected through available literature, published reports and Internet search.

5. Building Emission Factors: The model to arrive at city specific CO_2 emission factor and entropy generation factors would require accounting for CO_2 emissions and entropy generation from the building constituents, and the following constituents have been considered in some detail:

1. Cement
2. Reinforcement Steel
3. Brick

As regards the emissions and entropy generation from sand and aggregate, no attempt was made to study them further, other than the total volume impact in generic terms on the environment. CO_2 emissions and entropy generation from cement has been considered in the following few paragraphs. It is to be noted here that cement and concrete technology in itself is a vast field, and it is not possible even to scratch on the surface of it, even if one wanted to do so. Some of the basic and elementary concepts which are essential to arrive at some understanding of the subject relevant to the topic would be attempted to be dealt with.

5.1 Cement: Cement has been accounted for 5-7% of the total global level CO_2 emissions, and hence is a major contributor to the global warming. Cement has been studied extensively from pollution and CO_2 emissions perspective. The IPCC has framed certain standards which have been followed here for calculating the CO_2 emissions. Cement is produced by heating a mixture of limestone ($CaCO_3$) and clay ($SiO_2+Al_2O_3+\ldots$) and other similar material to a temperature of about 1450^0C. This produces clinker. (Taylor, 1997). The portland cement clinker consists of at least two-thirds by mass of calcium silicates $(CaO)_3Si0_2$ and $(CaO)_2Si0_2$, the remainder containing aluminum oxide (AI_2O_3), iron oxide (Fe_20_3) and other oxides. The ratio by mass ($CaO/Si0_2$) should not be less than 2.0. The clinker is an artificial mix and does not occur naturally (Hewlett, 2004). The clinker is then cooled, mixed with calcium sulphate ($CaSO_4$), mainly derived from gypsum ($CaSO_4.2H_2O$) finely ground to make cement. Tricalcium silicate ($(CaO)_3.SiO_2$), also written as C_3S, known as Alite, constitutes 50-70% of cement. Dicalcium silicate $(CaO)_2.SiO_2$, also written as C_2S, known as Belite, constitutes 15-30% of cement. Tricalcium aluminate ($(CaO)_3.Al_2O_3$), also written as C_3A, constitutes 5-10% of cement. The fourth major component of cement is ferrite, known as tetracalcium aluminoferrite ($(CaO)_4.Al_2O_3$ $.Fe_2O_3$), also written as C_4AF, constitutes 5-15% of cement (Taylor, 1997). Cement is produced for many purposes. The general purpose cement used in construction is called Ordinary Portland Cement (OPC).

As reported by USGS (2014), the world produced 4000 Million Tons (MT) of cement in 2013. India ranks second in the world in cement production. Its production for 2014 was 280 MT. India has 188 large cement plant accounting for 97% of the total production with an installed capacity of 358.9 MTPA (Million Tons per Annum). There are 365 mini plants with installed capacity of 11.1 MTPA. The demand was 324 MT in 2014-15, with per capita consumption of 190 kg. The per capita. world consumption of cement is 500 kg (IBEF, 2015). The following abbreviations shall be used for the chemical components of cement/ clinker:

$$C=CaO;\ A=Al_2O_3;\ S=SiO_2;\ M=MgO;\ F=Fe_2O_3;\ f=FeO; \qquad (1)$$

5.1.1. CO_2 Emissions from Cement: CO_2 is produced in cement manufacturing mainly in the clinker production stage where $CaCO_3$ is heated (calcined) to convert it to lime (CaO). CO_2 is also released from the fossil fuel used (coal, natural gas etc.). Additionally, the electricity used in the cement plant would also have its associated CO_2 emission levels. In this paragraph, the CO_2 emission during clinker production alone is considered. Normally, the other factors such as energy contributing to CO_2 are accounted for in the energy sector only. The calcination reaction in clinker formation is given by:

$$CaCO_3 = CaO + CO_2 \qquad (2)$$

This reaction occurs at a temperature of 600^0-900^0C at the cooler upper end of the kiln. At the hotter lower end of the kiln, CaO reacts with silica, alumina, and iron oxides to produce clinker. As per IPCC Guidelines, the Emission Factor ($EF_{Clinker}$) is calculated as below:

$$EF_{clinker} = \text{fraction CaO} \bullet (44.01 \text{ g/mole CO2}/ 56.08 \text{ g/mole CaO}) \quad (3)$$

$$EF_{clinker} = \text{fraction CaO} \bullet 0.785 \quad (4)$$

The IPCC Guidelines recommends two possible methods for calculating the emission factor. The Tier 1 method uses the IPCC default value for the fraction of lime in clinker, which is taken as 64.6%. The Equation 4 now becomes:

$$EF_{clinker} = 0.646 \bullet 0.785 = 0.507 \quad (5)$$

Thus, the emission factor is 0.507 tons of CO_2/ton of clinker produced. Cement Kiln Dust (CKD) is a by-product of the kiln process. A portion of the dust is recovered and put back into the kiln for calcination. However, as per IPCC, there is little data available on CKD (Gibbs et al, 2000). IPCC gives the following equation for emission calculation incorporating CKD:

$$\text{Emissions} = EF_{clinker} \bullet \text{Clinker Production} \bullet \text{CKD Correction Factor} \quad (6)$$

The default CKD correction factor is 1.02. The actual CKD contribution could range from 1.5% to 8% in modern cement plants. (van Oss, 1998). As per IPCC, calculating CO_2 emission directly from cement production data is not a good practice. However, in absence of clinker production data, cement production data may be used. The suggested equation for calculating emissions from cement production include correction factors for international trade in clinker.

$$\text{Estimated Clinker Production} = \text{Cement Production} \bullet \text{Clinker Fraction}$$
$$- \text{Imported Clinker} + \text{Exported Clinker} \quad (7)$$

Clinker fraction suggested by IPCC (2000) is 95%. If imported and exported clinker are ignored, then the Equation 6 can be rewritten as:

$$\text{Emissions} = EF_{clinker} \bullet \text{Cement Production} \bullet \text{Clinker Fraction} \bullet \text{CKD Correction Factor} \quad (8)$$

Using Equation 5, the above expression can be rewritten as

$$\text{Emissions} = 0.507 \bullet \text{Cement Production} \bullet \text{Clinker Fraction} \bullet \text{CKD Correction Factor} \quad (9)$$

Using recommended clinker fraction (95%) and CKD correction factor (1.02), the equation 9 becomes:

$$\text{Emissions} = 0.507 \bullet \text{Cement Production} \bullet \text{Clinker Fraction} \bullet \text{CKD Correction Factor}$$

$$= 0.507 \bullet \text{Cement Production} \bullet 0.95 \bullet 1.02$$

$$= 0.491 \bullet \text{Cement Production} \qquad (10)$$

Therefore, 0.49 tons of CO_2 is emitted per ton of cement production from clinker process alone. The other part of the CO_2 emission comes from burning of the fossil fuels. This aspect shall be examined in some detail in the next section. However, before that, the entropy of the clinker formation shall be examined in some detail.

5.1.2. Entropy Generation in Cement Manufacturing:

There are four sources of heat in the cement manufacturing process namely:

1. Enthalpies of reaction in the clinker calcination process
2. Burning of fuel
3. Heat of hydration of cement
4. Carbonation of cement/concrete

Each of these need to be examined in some detail to arrive at a reasonable estimation of entropy generation from cement/concrete.

Enthalpies of Reaction: Though the main reaction in clinker formation is given by Equation 1 above, there are several reactions happening within the kiln. The per kg standard enthalpy of reactions involved in calcination process are given below:

Table No. A3.2: Enthalpies of Reaction in Clinker Formation

Sl. No	Reaction in the Kiln	Standard Enthalpy ($KJ\ kg^{-1}$)	Enthalpy at Kiln Temperature ($KJ\ kg^{-1}$) per Kg of cement clinker
1.	$CaCO_3 = CaO + CO_2$	+1782	+2138
2.	AS_4H (pyrophyllite) = α-Al_2O_3 + $4SiO_2$ (quartz) + H_2O (g)	+224	+34
3.	AS2H2 (kaolinite) = α-Al2O3 + 2SiO2 (quartz) + 2H2O (g)	+538	+21
4.	2FeO • OH (goethite) = α-Fe2O3 + H2O (g)	+254	+8
5.	3CaO + SiO2 (quartz) = C3S	-734	-333
6.	2CaO + SiO2 (quartz) = β-C2S	-495	-98
7.	3CaO +α-Al2O3 = C3A	-27	-3
8.	6CaO + 2α -A12O3 +α-Fe2O3 = C6A2F	-157	-10
9.	4CaO + α-Al2O3 + α-Fe2O3 = C4AF	-105	0
	TOTAL	**+1280**	**+1757**

The above table has been adopted from Taylor (1997) by combining his Table 3.1 and 3.2. However, Taylor has not shown the enthalpy of formation of C_4AF (please see sl no. 9 of the table above) at kiln temperature. The overall reaction is endothermic. An amount of 1757 kJ Kg^{-1} of heat is required for the reaction to happen. This translates to about 420 Kcal/kg of heat requirement for the reaction. Hewlett (2004) estimated the heat balance of the clinker formation processes. He calls this heat ***theoretical heat requirement for clinker burning***. According to him, about 400 kcal/kg heat is the theoretical requirement. The actual heat requirement would vary as per the kiln type and process as well as the temperatures achieved inside the kiln. The standard heat of formation at 298K would change at higher temperatures due to change in heat capacities of the substances involved. Therefore, the **theoretical energy consumed per kg of cement clinker is taken to be 1757 kJ kg^{-1}**.

Burning of Fuel: Though the theoretical heat energy required for clinker formation is only 1757 kJ kg^{-1}, in reality a much larger amount of energy is consumed. The energy required for burning of clinker, an endothermic process, is to be supplied externally. As per Hewlett (2004), the heat balance for dry and wet kiln processes shows that the energy expenditure varies from 857 to 1382 kcal kg^{-1}, This translates to 3585.69 MJ/ton for dry process and 5782.29 MJ/ton for wet process of clinker production. In another study by Ohunakin et al (2013), the energies for dry and wet processes were worked from 2003 to 2011. The findings are summarized in the table below:

Table No. A3.3: Energies of Dry and Wet Cement Processes

Manufacturing Process	Combustion (MJ/Ton)	Electrical (MJ/ton)	Manual (MJ/Ton)	Total (MJ/ton)
Dry	3098.97	474.68	36.1	**3609.75**
Wet	5451.79	504.23	39.57	**5995.59**

Ohunakin et al (2013) found the average combustion energy (from fossil fuels) to be 3098.97 MJ/ton of cement produced from dry process and 5451.79 MJ/ton from wet process. Without actually identifying which cement comes from which process, it would not be possible to assign the actual energy values associated with the manufacturing process. Since the processes are varied, between the wet and dry processes, and assuming that every plant today would strive to conserve energy, it would be safe to assume that most factories use dry process, and we may assume a figure of **3100 MJ/ton** of cement to be the combustion energy used, and **475 MJ/ton** of electrical energy used in the cement manufacturing (dry) process.

The whole of 3100 MJ/ton has CO_2 emission associated with it, as fossil fuel is used to obtain this energy. However, the actual footprint size would depend upon the kind of fuel used. Natural gas, for example, would have lesser foot print for the same energy requirement than coal. The theoretical heat requirement of combustion was arrived at 1751 kJ kg^{-1} of clinker produced. This also translates to 1751 MJ/ton of clinker produced. Therefore, of the total combustion energy supplied in the cement plant, 1751 MJ/ton is used in the chemical reaction, ad the rest of the heat can be said to be lost to the surroundings. Therefore,

$$\text{Heat Lost} = \text{Heat supplied} – \text{Heat of Formation of clinker} \quad (12)$$

$$= 3100 – 1751 \text{ MJ/ton}$$

$$= \mathbf{1349\ MJ/ton}$$

As regards, the electrical energy used in the cement manufacturing, as per the authors (Ohunakin et al, 2013), the efficiencies of electrical equipment is taken to be 80%. Therefore, to consume 475 MJ/ton electrical energy, the supply side energy would be:

$$\text{Input Electrical Energy} = \text{Energy used/efficiency}$$

$$= 475/0.80$$

$$= 593.75 \text{ MJ/ton}$$

$$\sim 594 \text{ MJ/ton} \quad (13)$$

The input electrical energy has its own CO_2 emission factor, as well as entropy generation. Assuming a grid efficiency of 94.28% (CRISIL), and power plant efficiency of 33%, and further assuming that 70% of the power comes from thermal plants [*as of August, 2015189.3 GW is the total thermal installed capacity against a total of 272.5 GW installed capacity of all types of power plants in India (IBEF, 2015)*], the energy required at the power plant side is given by:

$$EE_{plant} = 0.70 \bullet EE_{input} \bullet 1/(\eta_{plant} \bullet \eta_{grid})$$

$$= 0.70 \bullet 594 \bullet 1/(0.33 \bullet 0.9428)$$

$$= 1366.44 \text{ MJ/ton} =\sim 1366 \text{ MJ/ton} \quad (14)$$

Energy lost from power plant to cement plant = 1366 - 475 MJ/ton

= **891 MJ/ton** (15)

The carbon footprint of the energy used can be calculated from the value arrived at Equation A3.13 by using the WRI Toolkit (Gillenwater, 2005). The CO_2 emission is given by the two equations mentioned below:

$$Eco_2 = A_{f,m} \bullet F_{c,m} \bullet F_{ox} \bullet (44/12) \quad (16)$$

$$A_{f,h} = A_{f,m} \bullet H_m \quad (17)$$

where,

Eco_2	=	Mass Emissions of CO_2 in metric tons	(or Kg)
$A_{f,m}$	=	Mass of fuel consumed in metric tons	(or Kg)
$F_{c,m}$	=	Carbon content of fuel on mass basis (ton C/ton fuel)	(or Kg C/Kg)
F_{ox}	=	Oxidation factor (IPCC recommended value 0.98)	
$A_{f,h}$	=	Heat content of fuel consumed in GJ	(or MJ)
H_m	=	Calorific value of fuel on mass basis (GJ/ton)	(or MJ/Kg)

$A_{f,h}$ is value arrived at in Equation 12. H_m for Indian coal is prescribed by IPCC as 19.98 MJ kg^{-1} or GJ/ton. $F_{c,m}$ varies considerably from site to site. This value was arrived at by averaging %C values of coal used in 10 power plants across India in a study by Mittal el al (2012). The average carbon content of coal used by Indian power plants comes to 34.75%. Since the factor is unit less, a value of 0.3475 was used. Putting these values in Equation 15 and 16, we arrive at two important emission factors for coal in India namely:

$$Eco_2 = 1.249 \bullet A_{f,m} \quad (18)$$

$$Eco_2 = 0.0625 \bullet A_{f,h} \quad (19)$$

where $A_{f,m}$ is the amount of coal used in kg or metric tons. Eco_2 is in similar units as well.

$A_{f,h}$ is the amount of coal based energy in GJ or MJ. Eco_2 is in tons or kg.

If the required energy E_{input} is known, and the fuel supply has to happen from a carbon source, then the amount of CO_2 released can be worked by the formula:

$$Eco_2 = (44 / 12) \bullet E_{input} / 32.792$$

$$Eco_2 = 0.11182 \text{ kg MJ}^{-1} \quad (\text{ton GJ}^{-1}) \tag{20}$$

If E_{input} is in MJ or GJ, then Eco_2 is in kg or tons. This assumes that 32.792 MJ energy is released in burning 1 ton of carbon.

Hewlett (2004) has worked out the CO_2 emission from 1 kg of cement manufacturing, assuming 1.209 kg of limestone ($CaCO_3$) input, 2930 kJ kg^{-1} of thermal energy for clinker burning, and 432 kJ kg^{-1} of electrical energy at 40% generation efficiency leading to production of 1080 kJ kg^{-1} of energy in the power plant. Working the equation A3.10 backwards, it can be easily found out that it would take 1.116 kg of limestone ($CaCO_3$) to manufacture 1 kg of cement, going by the IPCC guidelines. The CO_2 emission for cement as worked out by Hewlett (2004), and the by the author based on Equations 10, 11, 14 & 20 are compiled below in tabular format. All calculations are for 1 metric ton of cement produced.

Table No. A3.4:A Comparative Evaluation of Energy Use in Cement Manufacture

	Clinker Formation		Combustion Energy		Electrical Energy			Total CO_2 (ton)
	$CaCO_3$ (ton)	CO_2 (ton)	Energy (MJ)	CO_2 (ton)	Energy	η	CO_2 (ton)	
Hewlett	1.209	0.532	2930	0.3276	432	0.40	0.1208	0.980
Author	1.116	0.491	3100	0.3466	475	0.25	0.1527	0.990

As per the ICE database, Portland cement with 94% clinker cement has embodied energy of 5.50 MJ/kg and embodied CO_2 emission 0.95 kg.

Heat of Hydration of Cement: When water is added to cement, heat is liberated. The amount of heat liberated and consequent rise in temperature and duration are all functions of composition of cement and its fineness (Verbeck & Foster, 1950). The rate of release of heat may be seen in the diagram below (Taylor, 1997). The heat released in hydration of cement was studied in terms of its various constituents such as C_3S, C_2S, C_3A, C_4AF, and linear best fit relationships were deduced by Verbeck & Foster (1950). Total heat of hydration is sum of the individual heats of hydration of the constituents. Hewlett (2004) gave enthalpies of complete hydration which are quoted here from his Table No. 6.3.

Table No. A3.5: Enthalpies of Hydration of Cement

Sl. No.	**Starting Phase**	**Reaction Product**	**Enthalpy (KJ kg^{-1})**
1.	C_3S	C-S-H + CH	520
2.	β-C_2S	C-S-H + CH	260
3.	C_3A	C_4AH_{19}	1160
4.	C_3A	C_3AH_6	910
5.	C_3A	C_4ASH_{12}	1140
6.	C_3A	$C_6AS_3H_{32}$	1670
7.	C_4AS	C_3AFH_6	420
	TOTAL		**6080**

Therefore, as per the additive principles mentioned above, the total heat released in complete hydration of cement which may take more than 13 years or so (Taylor, 1997), can be taken to be 6080 kJ kg^{-1} (Hewlett, 2004). This translates to 6080 MJ/ton of energy.

Carbonation of Cement/ Concrete: Carboration is the reverse process of calcination, which is given in Equation 2. The equation can be rewritten as:

$$CaO + CO_2 = CaCO_3 \qquad \Delta H = -178.2 \text{ kJ mole}^{-1} \qquad (21)$$

The heat of carbonation is adopted from the standard enthalpy of calcination provided by Hewlett (2004). The carbonation process, in realty, is a complex phenomenon depending upon the water/cement ratio, type of cement and the environmental conditions enveloping the concrete. Björn Lagerblad (2005) has studied in detail the CO_2 uptake during concrete life cycle.

Talukdar et al (2012, 2012[a,b]) have developed carbonation models in context of global climate change. Carbonation is now largely seen as carbon sequestration by concrete (Stanmore & Gilot, 2005, El-Hassan & Shao, 2014). The focus of the study here is to estimate the amount of CO_2 that can be sequestered in concrete during its life cycle and the associated heat generation. Lagerblad (2005) has given the following equation for estimating CO_2 uptake by concrete assuming that 25% of CaO in concrete would never get sequestered (Taylor, 1997). Lagerblad's equation is adopted in the following format:

$$\Psi_{CO2} = 0.75 \bullet C \bullet CaO \bullet (Mco_2 / Mcao) \quad (Kg / m^2) \tag{22}$$

Where,

Ψ_{CO2} = Sequestered CO_2 in Kg

0.75 = Fraction of carbonizable CaO in concrete

C = Amount of Portland cement in concrete per m^2

CaO = Fraction by weight of CaO in cement

Mco_2 = Molecular Mass of CO2

Mcao = Molecular Mass of CaO

Taking the default value of lime in clinker to be 64.6% as per IPCC, and again default value clinker in cement to 0.95 as per IPCC, the value of CaO in 1 kg of cement works out to be 0.646 ● 0.95 = 0.614 kg. This value, however, as per Hewlett (2004) would work out to 0.677 (=1.209 ● 56 / 100) where 1.209 kg is the amount of $CaCO_3$ required to manufacture 1 kg of cement, 56 is the molecular mass of CaO and 100 is the molecular mass of $CaCO_3$. However, we shall use the value of 0.614 kg CaO per Kg of cement for further calculations.

As per the information gathered from PWD, Assam, 1 m^3 of cement weighs 1440 kg, and for a mix of 1:2:4 of concrete of 1 m^3, about 310 kg of cement is required. However, the concrete volume for 1 m^2 construction works out to be about 0.9 m^3, which translates to 294 kg of cement, as per PWD. Additionally cement is used in brick work and cement plastering. Again, about 75 bricks are required per m^2 of construction, for which typically 12.50 kg cement are required to join the bricks, and another 10 kg to plaster both sides of the wall (5 inch wall with 6 mm plaster). Therefore, the total cement required for constructing 1 m^2 of built up space is as follows:

Table No. A3.6: Cement Requirement for 1 m^2 built up space and CO_2 Emission

	Concrete (Kg)	Brick Joining (Kg)	Wall Plastering (Kg)	Total (Kg)	Associated CO_2 Emission (Kg)	Sequestered CO_2 Ψ_{CO2} (Kg)
GF	294	12.50	10	**316.5**	**313.34**	**114.52**
OF	196	12.50	10	**218.5**	**216.32**	**79.06**
AT	122	12.50	10	**144.5**	**143.06**	**52.28**

Note: *1 kg of cement has been assumed to produce 0.99 kg of CO_2 emission directly and indirectly.*

Thus, from the table above, it is seen that for 1 m^2 construction is responsible for releasing 313.34 kg of CO_2 at the GF level. However, in the long term about 37% of the CO_2 emitted is sequestered. Now let us work out the amount of heat released in the carbonation process. The heat of carbonation given in Equation 21 is per mole of $CaCO_3$, which translates to 1782 kJ Kg^{-1} of $CaCO_3$. Assuming that 1.116 kg of $CaCO_3$ (limestone) is used to manufacture 1 kg of cement, the total heat of carbonation that might get released in the process per m^2 of construction is given in the Table below:

Table No. A3.7: Heat of Carbonation per 1 m^2 of built up

	Concrete (Kg)	Brick Joining (Kg)	Wall Plastering (Kg)	Total (Kg)	Associated $CaCO_3$ (Kg)	Heat Released (MJ m^{-2})
GF	294	12.50	10	**316.5**	**353.21**	**629.43**
OF	196	12.50	10	**218.5**	**243.85**	**434.53**
AT	122	12.50	10	**144.5**	**161.26**	**287.37**

5.2 Brick: Brick is another construction material, and considered one of the most polluting industries in India. Brick is manufactured in brick fields using clay and other suitable material mostly by hand moulding and firing in a kiln. Most common brick kilns in the North eastern India are found to be Fixed Chimney Bull's Trench Kiln (FCBTK). The nergy is mostly derived from either coal or firewood. Several studies on Specific Energy Consumption (SEC) in brick manufacturing in India have been done, noted among them being Maithel (2003) and Amaha & Pydi (2014). According to Maithel (2003), the SEC in brick manufacturing per kg was found to be 1.12±0.03 MJ/kg. Further, according to the author, 20-40% of the energy is used for irreversible chemical changes, and the rest gets wasted in heating the surroundings and the escaping flue gases. Therefore, it can be assumed that 30% of the energy on an average is used for irreversible chemical changes. The baking happens from 660^0C to 1400^0C. Bureau of Energy Efficiency, Govt. of India (2010) carried out energy audit of 22 brick kilns in Varanasi cluster in 2010. The SEC varied from 1.10234 MJ/kg to 1.60866 MJ/kg in the cluster with a mean of 1.30±0.031 MJ/Kg. We may, therefore, assume a mean thermal SEC of 1.331 MJ/kg, keeping the energy on the higher limit. Assuming a brick would weigh 3.0 kg, the associated energy per brick would be 3.993 MJ per brick, of which 1.1979 MJ per brick is used in chemical changes and 2.7951 MJ per brick is lost to the surroundings. Assuming 75 bricks per m^2 used in construction, these figures work out to be:

Energy required per m^2: 294.475 MJ m^{-2} (23)

Energy lost: 209.633 MJ m^{-2} (24)

The CO_2 emission for bricks can be worked out using Equation 20, using equation 23 above, the per m^2 direct emission from bricks comes to:

CO_2 Emission: 0.446 kg per brick (25)

CO_2 Emission: 33.49 kg m^{-2} (26)

However, as per the ICE database, the embedded energy per kg of brick is 3.0 MJ kg^{-1}, and the associated CO_2 emission is 0.24 kg. Ice assumes brick weight of 2.3 kg. Accordingly, the energy per brick comes to 6.9 MJ, and CO_2 emission comes to 0.55 kg.

5.3 Steel: Steel used in reinforcement has been only attempted to be estimated in this exercise. No attempt was done to evaluate its associated heat and CO_2 emission through a Tier 2 methodology. As per the ICE database, 100% virgin steel rod and bar have the following characteristics of embodied energy and CO_2 emission:

Embodied energy: 29.2 MJ per kg (27)

CO_2 Emission: 2.77 kg per kg (28)

Further, the US Department of Energy (USDE) worked out theoretical requirement of energy in various process in iron and steel making (Fruehan et al, 2000). According to this study, energy requirement for producing steel bar is at best 6893 MJ per ton. Therefore, it can be assumed that rest of the energy is likely to be lost to the surroundings. Working from Equation 26, the energy lost in steel bar making may be assumed to be as follows:

Embodied energy:	29.2 MJ per kg
Theoretical energy:	6.9 MJ per kg
Energy Lost:	22.3 MJ per kg

(29)

The PWD, Assam provided the requirement of steel in per m^2 floor area, and accordingly the embodied energy and emission values have been worked out per m^2 for steel as given in the Table below:

Table No. A3.8: Energy and Emission Values for Steel per 1 m^2

	Amount of Steel (Kg)	Associated Embodied Energy ($MJ\ m^{-2}$)	Energy Lost ($MJ\ m^{-2}$)	Associated CO_2 ($kg\ m^{-2}$)
GF	50	1460.00	1115.00	138.50
OF	30	876.00	669.00	83.10
AT	12.50	365.00	278.75	34.63

6. SUMMARY: The total input energy would be required to work out the embedded energy of the materials. Part of this energy would have been used to do work, and rest would have got dissipated as (sensible) heat. The direct and indirect sources of energy are enumerated below:

Table No. A3.9: Direct & Indirect Energy in Cement Processes

Sl. No.	Process	Energy (MJ/Ton)	Energy (MJ/kg)	Energy per m^2 Built up Area (MJ)			Eq/ Table Reference
				GF*	OF*	AT*	
1.	Heat in Cement Plant (Clinker)	3100	3.10	981.15	677.35	447.95	*Eq. 12*
2.	Heat in Power Generation	1366	1.37	433.61	299.35	197.97	*Eq 15*
3.	Heat of Hydration	6080	6.08	1924.32	1328.48	878.56	*Table No. A3.5*
4.	Heat of Carbonation	1989	1.99	629.84	434.60	287.56	*Table No. A3.7*
5.	Energy used in steel bar	29200	29.20	1460.00	876.00	365.00	*Table No. A3.8*
6.	Energy used in brick	1300	1.30	294.48	294.48	294.48	*Eq 23*
4.	**Total Indirect Energy** (1+2+5+6)	**34966**	**34.97**	**3169.24**	**2147.18**	**1305.4**	
5.	**Total Direct Energy** (3+4)	**8069**	**8.07**	**2554.16**	**1763.08**	**1166.12**	

* *Cement required per m^2 construction: 316.5 kg (GF), 218.5 kg (OF), 144.5 kg (AT) taken from Table No. A3.6*

The direct and indirect energy lost and resulting entropy generation at 298 K as well as CO_2 emission under various conditions for cement, brick and steel are summarized in the tables below. For cement, the energy waste has been summarized first.

Table No. A3.10: Direct & Indirect Waste Energy for Cement Processes

Sl. No.	Process	Energy (MJ/Ton)	Energy (MJ/kg)	Energy per m^2 Built up Area (MJ)			Eq/ Table Reference
				GF*	OF*	AT*	
1.	Heat lost in Cement Plant	1349	1.35	427.28	294.98	195.08	*Eq. 12*
2.	Heat lost in Power Generation	891	0.90	284.85	196.65	130.05	*Eq 15*
3.	Heat of Hydration	6080	6.08	1924.32	1328.48	878.56	*Table No. A3.5*
4.	Heat of Carbonation	1989	1.99	629.84	434.60	287.56	*Table No. A3.7*
4.	**Total Indirect Energy** (1+2)	**2240**	**2.25**	**712.13**	**491.63**	**325.13**	
5.	**Total Direct Energy** (3+4)	**8069**	**8.07**	**2554.16**	**1763.08**	**1166.12**	

* Cement required per m^2 construction: 316.5 kg (GF), 218.5 kg (OF), 144.5 kg (AT) taken from Table No. A3.6

Therefore, the total energy and associated entropy release (direct and indirect) per m^2 built up area is given in table below. The indirect entropy can be termed as **Entropy Import** or **Virtual Entropy w**ith respect to a site specific or boundary related economic processes.

Table No. A3.11: Entropy values per m^2 built up

Material used	Direct (per m^2)		Indirect (per m^2)		TOTAL (per m^2)	
	Energy Lost (MJ)	**Entropy (MJ K^{-1})**	**Energy Lost (MJ)**	**Entropy (MJ K^{-1})**	**Energy Lost (MJ)**	**Entropy (MJ K^{-1})**
Cement (GF)	2554.16	8.57	712.13	2.39	3266.29	**10.96**
Cement (OF)	1763.08	5.92	491.63	1.65	2254.71	**7.57**
Cement (AT)	1166.12	3.91	325.13	1.09	1491.25	**5.00**
Steel Bar (GF)			1115.00	3.74	1115.00	**3.74**
Steel Bar (OF)			669.00	2.24	669.00	**2.24**
Steel Bar (AT)			278.75	0.94	278.75	**0.94**
Brick (GF/OF/AT)			209.63	0.70	209.63	**0.70**
TOTAL(GF)	2554.16	8.57	2036.76	6.83	4590.92	15.41
TOTAL (OF)	1763.08	5.92	1370.26	4.60	3133.34	10.51
TOTAL (AT)	1166.12	3.91	813.51	2.73	1979.63	6.64

Similarly, for CO_2 emission, the values are given in the table below:

Table No. A3.12: CO_2 Emission values per m^2 Built up

Material Used	**Direct CO_2 (Kg m^{-2})**	**Indirect CO_2 (Kg m^{-2})**	**TOTAL CO_2 (Kg m^{-2})**
Cement (GF)		313.34	**313.34**
Cement (OF)		216.32	**216.32**
Cement (AT)		143.06	**143.06**
Steel Bar (GF)		138.50	**138.50**
Steel Bar (OF)		83.10	**83.10**
Steel Bar (AT)		34.63	**34.63**
Brick (GF/OF/AT)		33.49	**33.49**
TOTAL(GF)		485.33	**485.33**
TOTAL (OF)		332.91	**332.91**
TOTAL (AT)		211.18	**211.18**

Summary of construction type wise direct and indirect energy (including energy lost), entropy (of energy lost) and CO_2 emission factors per m^2 of built up space in Assam are given below:

Table No. A.13: Entropy and CO_2 Values per m^2 Built up

Type	Direct (per m^2)			Indirect (per m^2)			TOTAL (per m^2)		
	Energy (MJ)	Entropy (MJ K^{-1})	CO_2 (Kg)	Energy (MJ)	Entropy (MJ K^{-1})	CO_2 (Kg)	Energy (MJ)	Entropy (MJ K^{-1})	CO_2 (Kg)
GF	**2554.16**	**8.57**		**3169.24**	**6.83**	**484.33**	**5723.4**	**8.57**	**484.33**
OF	**1763.08**	**5.92**		**2147.18**	**4.6**	**332.91**	**3910.26**	**10.52**	**332.91**
AT	**1162.12**	**3.91**		**1305.4**	**2.73**	**211.18**	**2471.52**	**6.64**	**211.18**

Direct CO_2 emission at construction site by way of burning of fuels etc. was not worked due to insufficiency of secondary data, and extreme difficulties in real time data collection/ measurements.

APPENDIX-4: Population Growth Rates and Projections

The following formulae were used to arrive at the population growth rates. For years for which data at 10 year interval was available, the Decadenal Growth Rate (DGR) was calculated as (Seymour D. Bruce, 2004):

$$DGR = \frac{P_n - P_0}{P_0} * 100 \qquad (1)$$

Wherever, the data was not 10 year apart, the following formula was used:

$$DGR = \left[\left(\frac{P_n}{P_0} \right)^{\frac{10}{N}} - 1 \right] * 100 \qquad (2)$$

The Annual Growth Rate (AGR) was obtained using the formula

$$AGR = \left[\left(\frac{P_n}{P_0} \right)^{\frac{1}{N}} - 1 \right] * 100 \qquad (3)$$

The projected population in future was obtained using the formula

$$P_f = P_n \bullet (1 + R)^N \qquad (4)$$

where DGR = Decadenal Growth Rate in %

AGR = Annual Growth Rate in %

P_n = Population in the year n

P_0 = Population in the beginning

P_f = Projected Population in future time f

R = Annual Growth Rate in decimal (R= AGR/100)

N = Time interval between two populations P_n & P_o, and P_n and P_f

APPENDIX-5: Summary Tables of the Case Study

PART I
Sector Wise Entropy Generation and CO_2 Emission

Table No. A5.1: TOTAL OF ELECTRICITY CONSUMPTION

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1	2005-06	4.19	9.51		0.52	16.22
2	2006-07	4.79	10.89		0.59	18.57
3	2007-08	5.38	12.22		0.67	20.83
4	2008-09	6.10	13.87		0.76	23.65
5	2009-10	6.85	15.56		0.85	26.53
6	2010-11	7.44	16.89		0.92	28.81
7	2011-12	8.11	18.42		1.00	31.40
8	2012-13	8.51	19.33		1.05	32.96
9	2013-14	9.43	21.43		1.17	36.55
10	2014-15	10.17	23.11		1.26	39.40
11	2015-16	10.64	24.18		1.32	41.23
	TOTAL	**81.60**	**185.42**		**10.11**	**316.15**

Table No. A5.2: TOTAL OF FOSSIL FUELS

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1.	2010-11	22.72		0.846		26.83
2.	2011-12	23.27		0.869		27.49
3.	2012-13	24.23		0.905		28.63
4.	2013-14	23.45		0.877		27.71
5.	2014-15	22.38		0.840		26.46
6.	2015-16	22.48		0.845		26.59
	TOTAL	**138.53**		**5.182**		**163.71**

Table No. A5.3: TOTAL OF FUELWOOD

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy# (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1.	1911	0.270		0.010		0.319
2.	1967	5.100		0.180		5.975
3.	1986	5.110		0.180		5.985
4.	2003	6.140		0.220		7.209
5.	2010	4.220		0.150		4.949
6.	2015	4.810		0.170		5.636
	TOTAL	**25.650**		**0.910**		**30.073**

Table No. A5.4: TOTAL OF BUILDING MATERIALS

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1	2005	5.90	4.65		0.33	12.17
2	2006	13.30	10.49		0.75	27.45
3	2007	20.71	16.34		1.17	42.73
4	2008	28.11	22.18		1.59	58.01
5	2009	35.52	28.02		2.01	73.29
6	2010	42.93	33.86		2.42	88.57
7	2011	56.39	44.48		3.18	116.34
8	2012	69.85	55.10		3.94	144.11
9	2013	83.31	65.71		4.70	171.88
10	2014	96.77	76.33		5.46	199.65
11	2015	110.22	86.95		6.22	227.42
	TOTAL	**563.00**	**444.10**		**31.79**	**1,161.61**

Table No. A5.5: TOTAL OF FOREST LAND TO SETTLEMENT

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1.	1911			0.04		0.194
2.	1967			0.16		0.787
3.	1986			0.28		1.374
4.	2003			0.44		2.161
5.	2010			0.82		3.982
6.	2015			1.00		4.855
	TOTAL			**2.75**		**13.352**

Table No. A5.6: TOTAL OF CROPLAND

Sl. No.	Year	Entropy (ΔS TJK^{-1})		CO_2 Emission ($MtCO_2$)		Total Entropy (ΔS TJK^{-1})
		Direct	Indirect	Direct	Indirect	
1.	1911			0.030		0.1446
2.	1967			0.023		0.1131
3.	1986			0.021		0.1018
4.	2003			0.017		0.0819
5.	2010			0.007		0.0320
6.	2015			0.006		0.0279
	TOTAL			**0.103**		**0.5014**

PART II

Average Values of Entropy and CO_2 Emission from Energy Sources (2010-2015)

Table No. A5.7: Energy Values of Guwahati for 2010-2015

Year	Electricity (TJ)		Fossil Fuels (TJ)		Building Materials (TJ)	
	Energy Direct	Energy Indirect	Energy Direct	Energy Indirect	Energy Direct	Energy Indirect
2010-11	3204.30	5034.64	12,013.39		12789.82	15749.89
2011-12	3493.28	5488.69	12,350.30		16800.06	20688.26
2012-13	3666.75	5761.25	12,841.29		20810.30	25626.62
2013-14	4065.28	6387.43	12,488.32		24820.53	30564.99
2014-15	4383.06	6886.73	11,986.09		28830.77	35503.35
2015-16	4586.27	7206.01	12,101.00		32841.01	40441.71
Average	**3,899.82**	**6,127.46**	**12,296.73**		**22,815.41**	**28,095.80**

Table No. A5.8: Entropy Values of Guwahati for 2010-2015

Year	Electricity (TJK^{-1})		Fossil Fuels (TJK^{-1})		Building Materials (TJK^{-1})	
	Entropy Direct	Entropy Indirect	Entropy Direct	Entropy Indirect	Entropy Direct	Entropy Indirect
2010-11	7.44	16.89	22.72		42.93	33.86
2011-12	8.11	18.42	23.27		56.39	44.48
2012-13	8.51	19.33	24.23		69.85	55.10
2013-14	9.43	21.43	23.45		83.31	65.71
2014-15	10.17	23.11	22.38		96.77	76.33
2015-16	10.64	24.18	22.48		110.23	86.95
Average	**9.05**	**20.56**	**23.09**		**76.58**	**60.40**

Table No. A5.9: CO_2 Emission Values of Guwahati for 2010-2015

Year	Electricity ($MtCO_2$)		Fossil Fuels ($MtCO_2$)		Building Materials ($MtCO_2$)	
	CO_2 Direct	CO_2 Indirect	CO_2 Direct	CO_2 Indirect	CO_2 Direct	CO_2 Indirect
2010-11		0.92	0.85			2.42
2011-12		1.00	0.87			3.18
2012-13		1.05	0.91			3.94
2013-14		1.17	0.88			4.70
2014-15		1.26	0.84			5.46
2015-16		1.32	0.85			6.22
Average		**1.12**	**0.86**			**4.32**

Table No. A5.10: Input Energy Values, CO_2 & Entropy of Guwahati for 2010-2015

Year	**Total Input Energy**	TJK^{-1} **Entropy on Input Energy**	$MtCO_2$ **Total CO_2**	TJK^{-1} **CO_2 eq Entropy**	TJK^{-1} **Total Entropy**	TJ **Waste Energy on Input Energy**
2010-11	36002.22	80.92	4.19	20.34	101.26	30175.40
2011-12	42020.53	94.27	5.06	24.58	118.85	35417.50
2012-13	47895.91	107.17	5.90	28.69	135.86	40485.01
2013-14	53506.01	120.03	6.75	32.80	152.83	45544.23
2014-15	58759.23	131.99	7.56	36.76	168.75	50287.66
2015-16	64334.99	144.25	8.39	40.76	185.01	55133.65
Average	**50419.81**	**113.10**	**6.31**	**30.66**	**143.76**	**42840.58**

Table No. A5.11: Total Energy Values, CO_2 & Entropy of Guwahati for 2010-2015

Year	**Grand Totals Total Energy**	TJK^{-1} **Entropy**	$MtCO_2$ **Total CO_2**	TJK^{-1} **CO_2 eq Entropy**	TJK^{-1} **Total Entropy**	TJ **Waste Energy**
2010-11	48792.04	123.84	4.19	20.34	144.19	42967.65
2011-12	58820.59	150.66	5.06	24.58	175.24	52220.53
2012-13	68706.21	177.01	5.90	28.69	205.70	61299.11
2013-14	78326.54	203.34	6.75	32.80	236.14	70369.12
2014-15	87590.00	228.76	7.56	36.76	265.52	79123.63
2015-16	97175.99	254.48	8.39	40.76	295.24	87980.70
Average	**73235.23**	**189.68**	**6.31**	**30.66**	**220.34**	**65660.12**

PART III

Building Energy Usage

Table No. A5.12: Building Energy Usage of Guwahati 2010-2015

Total Input Energy (TJ)	Electricity		LPG	Kerosene	Fuelwood	Total Input Energy (TJ)
Year	**Direct**	**Indirect**	**Direct**	**Direct**	**Direct**	
2010-11	3204.30	5034.64	2240.49	5003.91	1382.75	16866.09
2011-12	3493.28	5488.69	2391.60	4983.65	1390.35	17747.57
2012-13	3666.75	5761.25	2434.16	4983.65	1434.57	18280.38
2013-14	4065.28	6387.43	2525.12	4983.65	1480.18	19441.66
2014-15	4383.06	6886.73	2587.20	4938.06	1527.25	20322.30
2015-16	4586.27	7206.01	2773.59	5236.88	1575.82	21378.57
TOTAL	**23398.94**	**36764.74**	**14952.16**	**30129.8**	**8790.92**	**114036.56**
Average	**3899.82**	**6127.46**	**2492.03**	**5021.63**	**1465.15**	**19006.09**

Table No. A5.13: Building Entropy Generation of Guwahati 2010-2015

ENTROPY (TJK^{-1})	Electricity		LPG	Kerosene	Fuelwood	Total Entropy (TJK^{-1})
Year	**Direct**	**Indirect**	**Direct**	**Direct**	**Direct**	
2010-11	7.44	16.89	2.71	10.41	4.22	41.67
2011-12	8.11	18.42	2.89	10.37	4.25	44.03
2012-13	8.51	19.33	2.94	10.37	4.38	45.53
2013-14	9.43	21.43	3.05	10.37	4.52	48.81
2014-15	10.17	23.11	3.13	10.27	4.66	51.34
2015-16	10.64	24.18	3.35	10.90	4.81	53.88
TOTAL	**54.3**	**123.37**	**18.07**	**62.69**	**26.84**	**285.27**
Average	**9.05**	**20.56**	**3.01**	**10.45**	**4.47**	**47.55**

Table No. A5.14: Building CO_2 Emission of Guwahati 2010-2015

CO_2 Emission (Mt CO_2)	Electricity		LPG	Kerosene	Fuelwood	Total CO_2 ($MtCO_2$)
Year	**Direct**	**Indirect**	**Direct**	**Direct**	**Direct**	
2010-11		0.92	0.14	0.36	0.15	1.57
2011-12		1.00	0.15	0.36	0.15	1.66
2012-13		1.05	0.15	0.36	0.16	1.72
2013-14		1.17	0.16	0.36	0.16	1.85
2014-15		1.26	0.16	0.36	0.17	1.95
2015-16		1.32	0.18	0.38	0.17	2.05
TOTAL		**6.72**	**0.94**	**2.18**	**0.96**	**10.80**
Average		**1.12**	**0.16**	**0.36**	**0.16**	**1.80**

Table No. A5.15: Total Building Energy Values, CO_2 & Entropy of Guwahati for 2010-2015

Year	Total Energy	TJK^{-1} Entropy	$MtCO_2$ Total CO_2	TJK^{-1} CO_2 eq Entropy	TJK^{-1} Total Entropy	Waste Energy (TJ)
2010-11	16866.09	41.67	1.57	7.63	49.30	14691.46
2011-12	17747.57	44.03	1.66	8.07	52.10	15525.08
2012-13	18280.38	45.53	1.72	8.36	53.89	16058.98
2013-14	19441.66	48.81	1.85	8.99	57.80	17224.70
2014-15	20322.30	51.34	1.95	9.48	60.82	18123.47
2015-16	21378.57	53.88	2.05	9.96	63.84	19025.21
Average	**19006.1**	**47.54**	**1.8**	**8.75**	**56.29**	**16774.82**
% Growth	**26.75**	**29.3**	**30.57**	**30.57**	**29.5**	**29.5**

Table No. A5.16: Total Building Per Capita Energy Values, CO_2 & Entropy of Guwahati for 2010-2015

Year	Population	Per Capita Energy (MJ)	Per Capita Entropy (MJK^{-1})	Per Capita CO_2 (tCO_2)	Per Capita Total Entropy (MJK^{-1})	Per Capita Waste Energy (MJ)
2010-11	963255	17509.48	43.26	1.63	51.18	15251.89
2011-12	968549	18323.87	45.46	1.71	53.79	16029.22
2012-13	999349	18292.29	45.56	1.72	53.92	16069.44
2013-14	1031128	18854.75	47.34	1.79	56.06	16704.71
2014-15	1063918	19101.38	48.26	1.83	57.16	17034.65
2015-16	1097751	19474.88	49.08	1.87	58.16	17331.08
Average		18592.77	46.49	1.76	55.05	16403.5
% Growth	**13.96**	**11.22**	**13.46**	**14.58**	**13.63**	**13.63**

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CHARTS

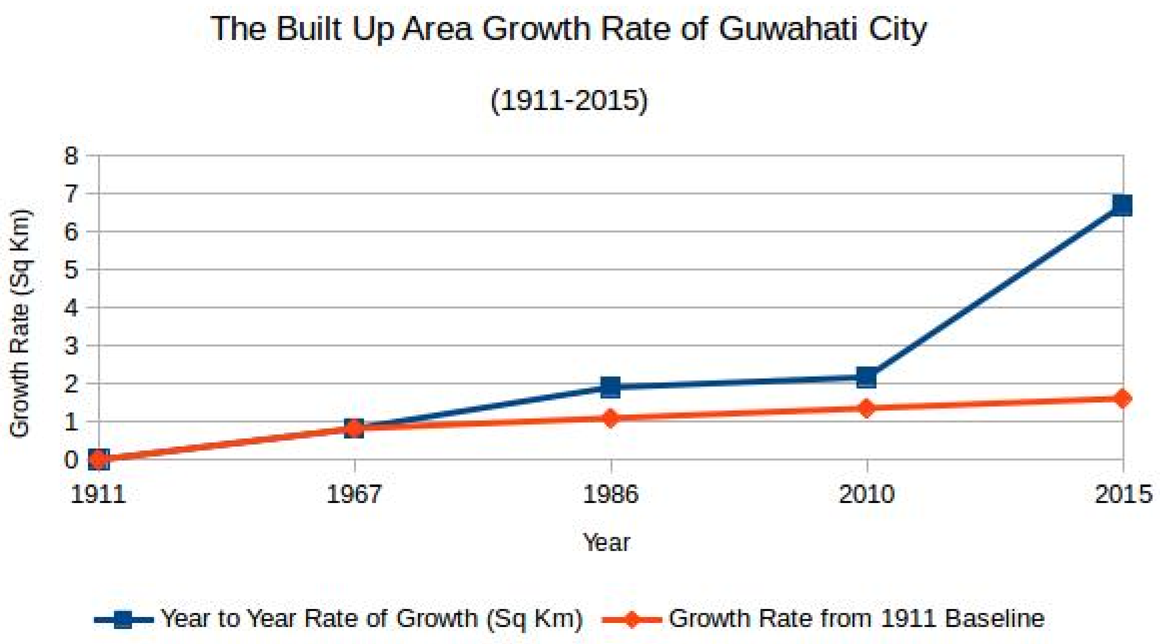


Chart No. 5.1: Guwahati City Built-up Growth Rate

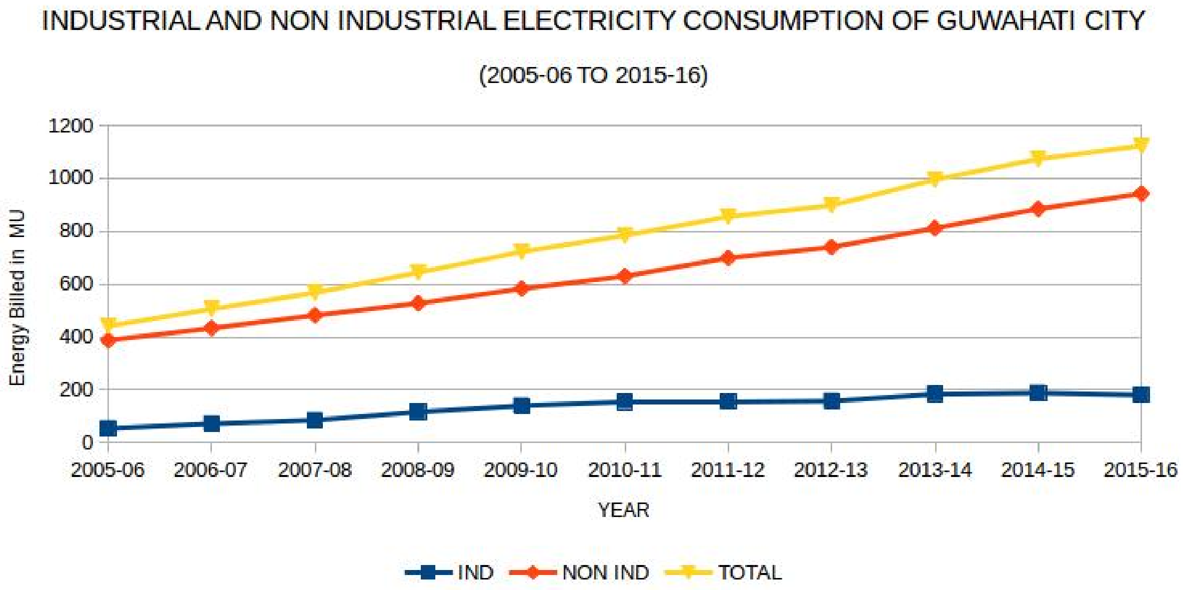


Chart No. 5.2A: Electricity Consumption Trends of Guwahati City

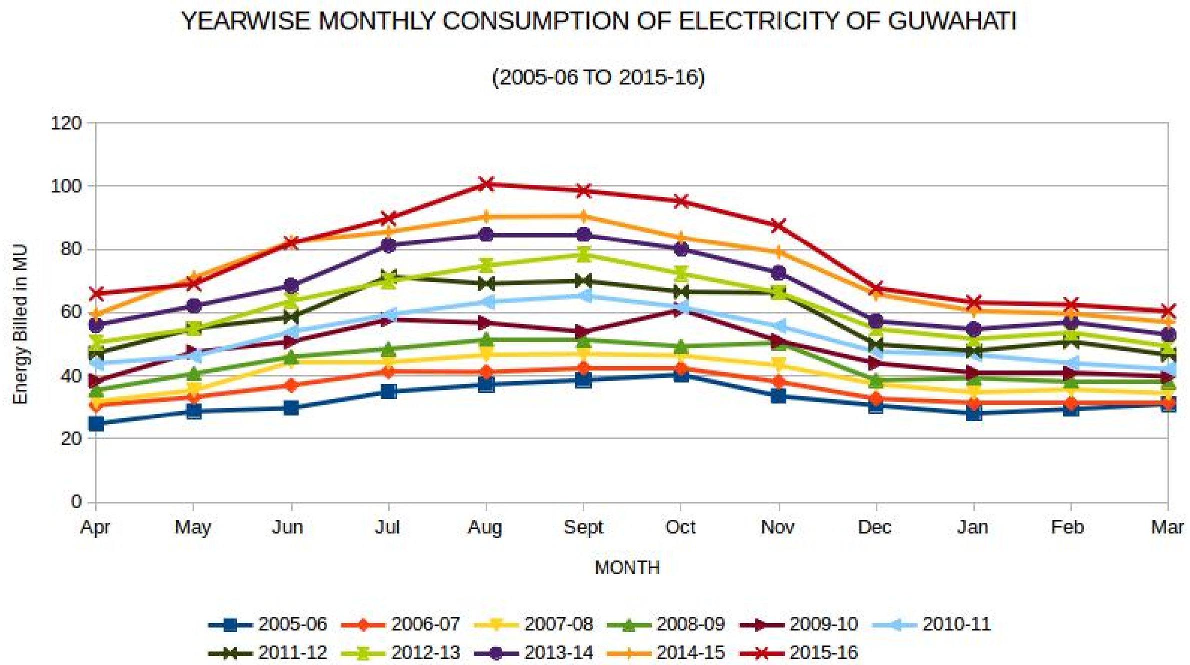


Chart No. 5.2B: Trends of Monthly Consumption of Electricity in Guwahati

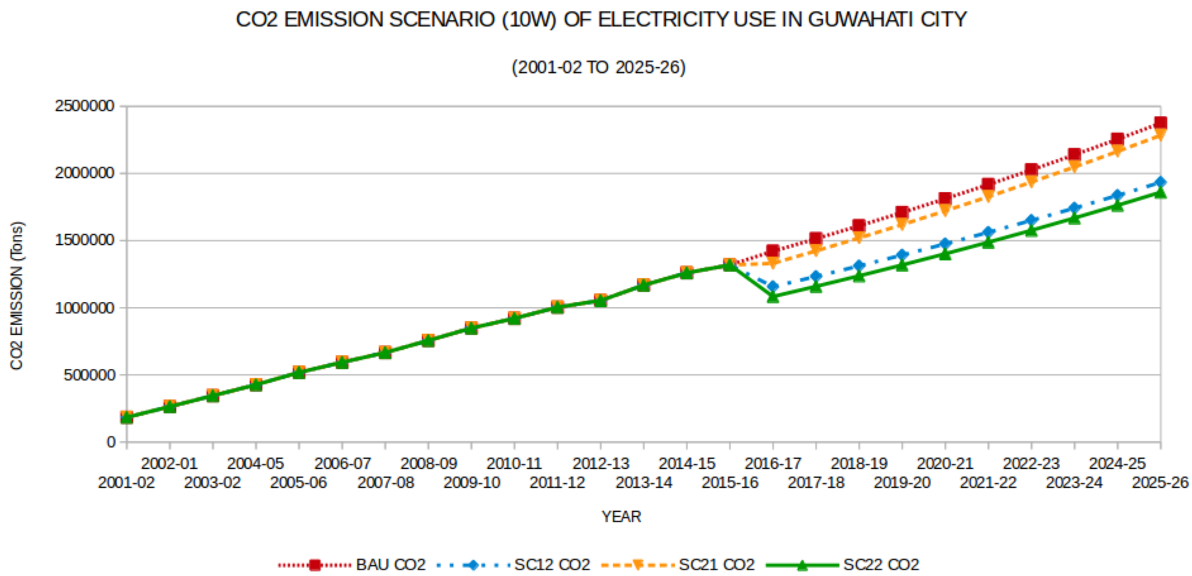


Chart No. 5.3A: CO_2 Emission Scenario (10W Reduction)

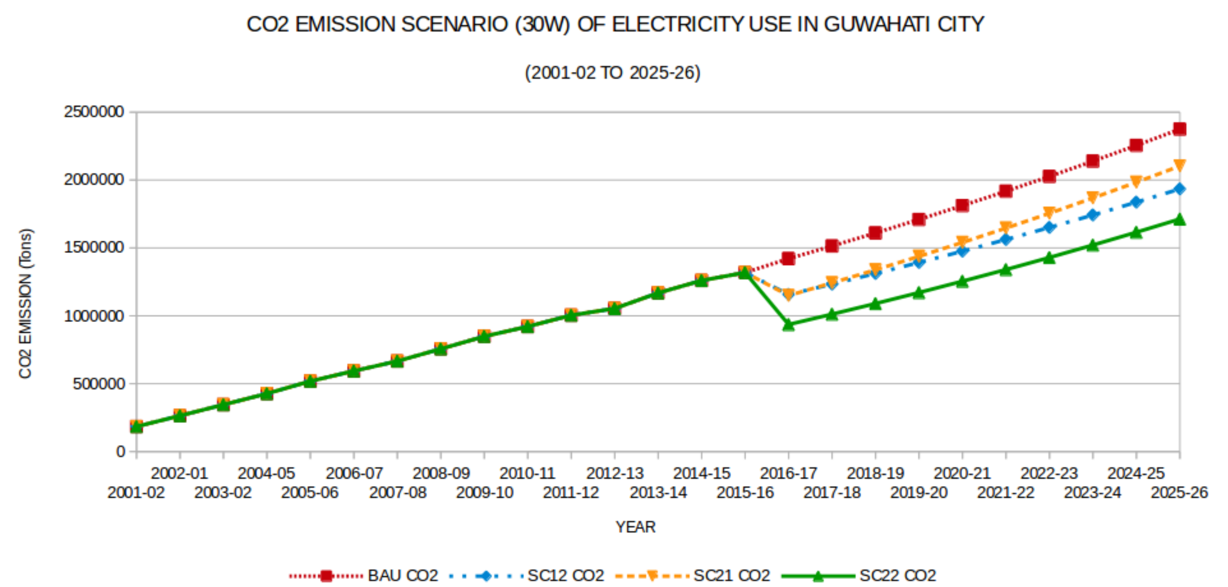


Chart No. 5.3B: CO_2 Emission Scenario (30W Reduction)

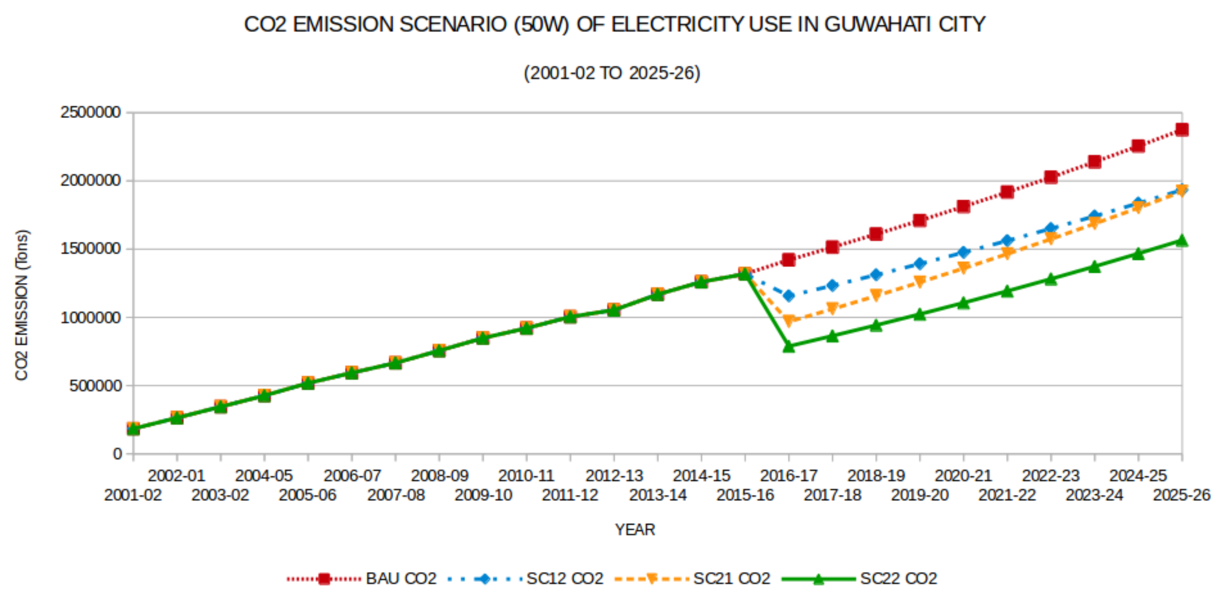


Chart No. 5.3C: CO_2 Emission Scenario (50W Reduction)

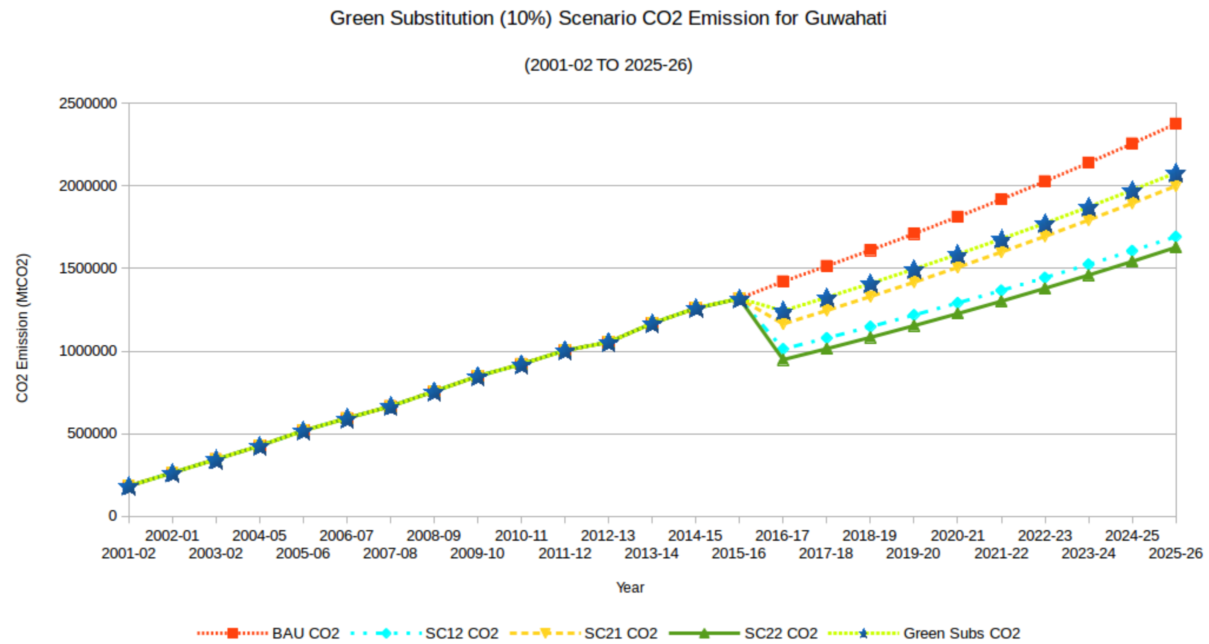


Chart No. 5.4A: CO_2 Emission Scenario (10W Reduction & 10% Green Power Substitution)

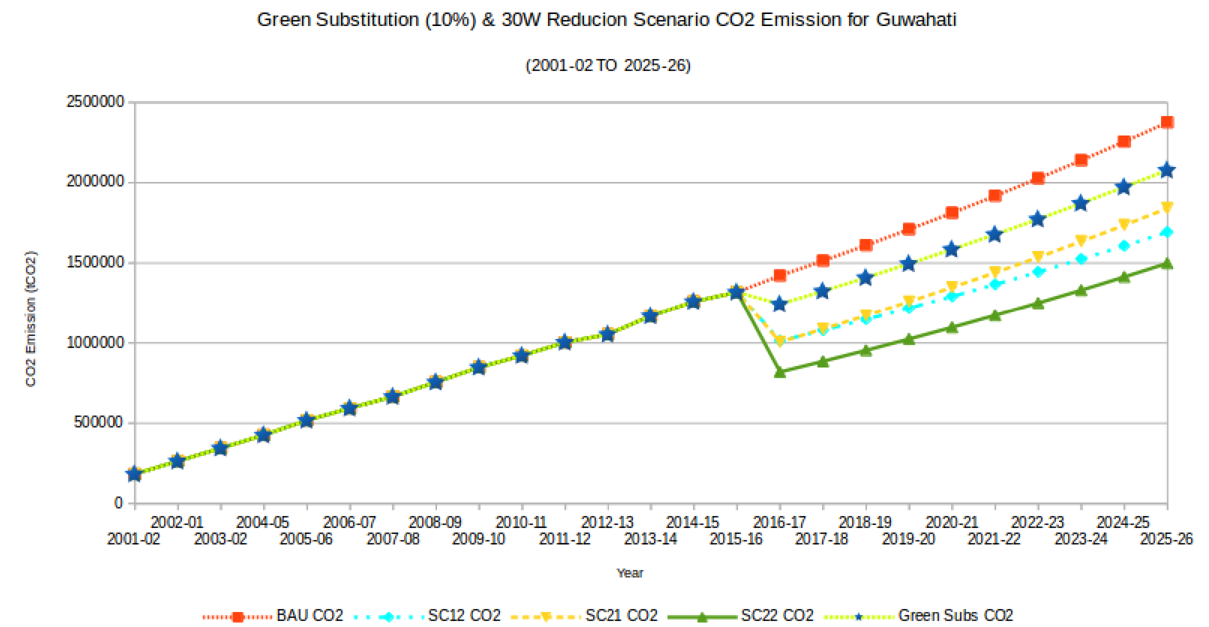


Chart No. 5.4B: CO_2 Emission Scenario (30W Reduction & 10% Green Power Substitution)

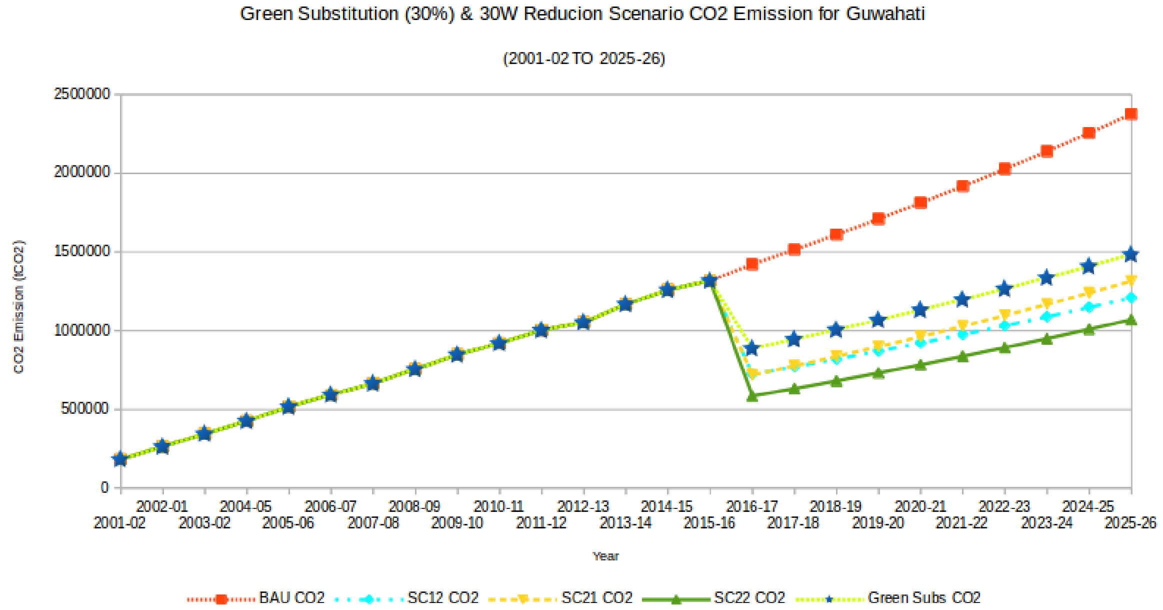


Chart No. 5.4C: CO_2 Emission Scenario (30W Reduction & 30% Green Power Substitution)

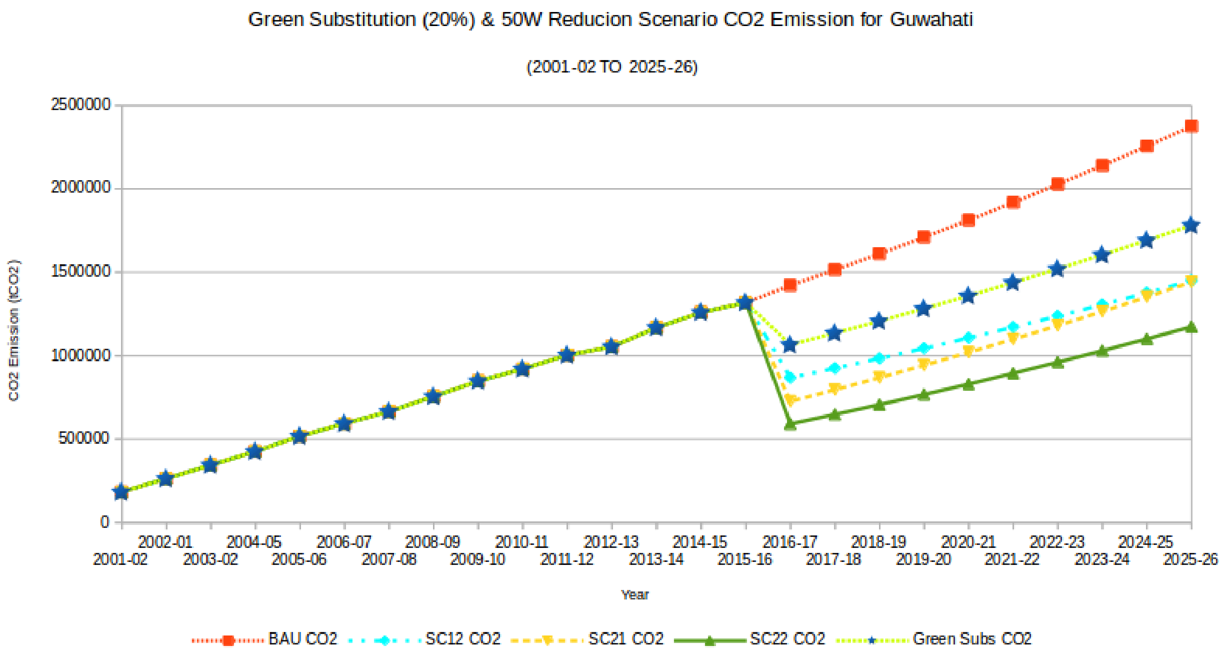


Chart No. 5.4D: CO_2 Emission Scenario (50W Reduction & 20% Green Power Substitution)

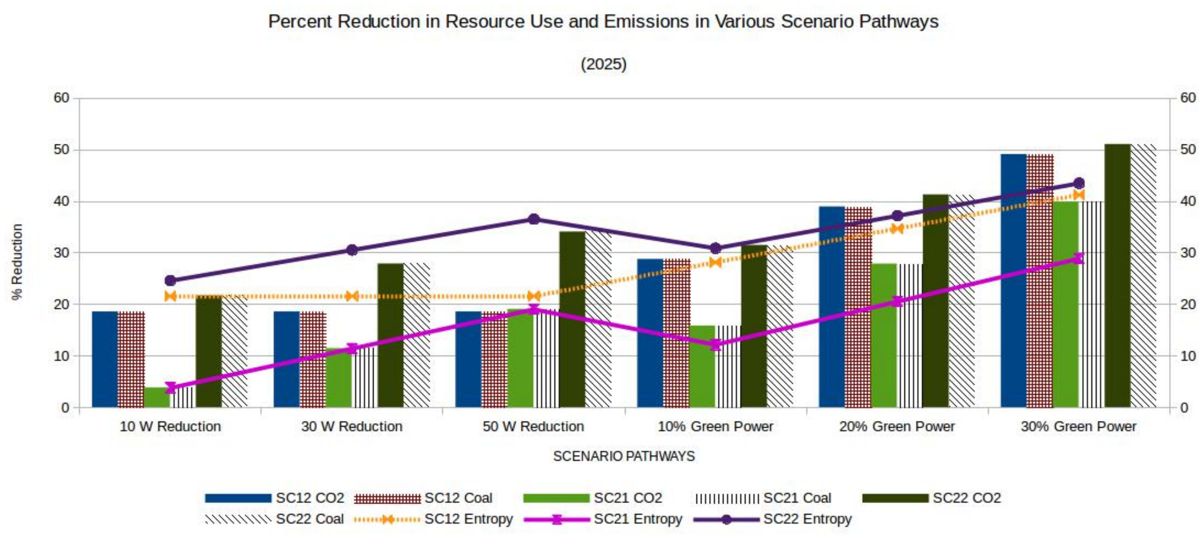


Chart No. 5.5A: % Reduction in Emissions in Various Scenario Pathways

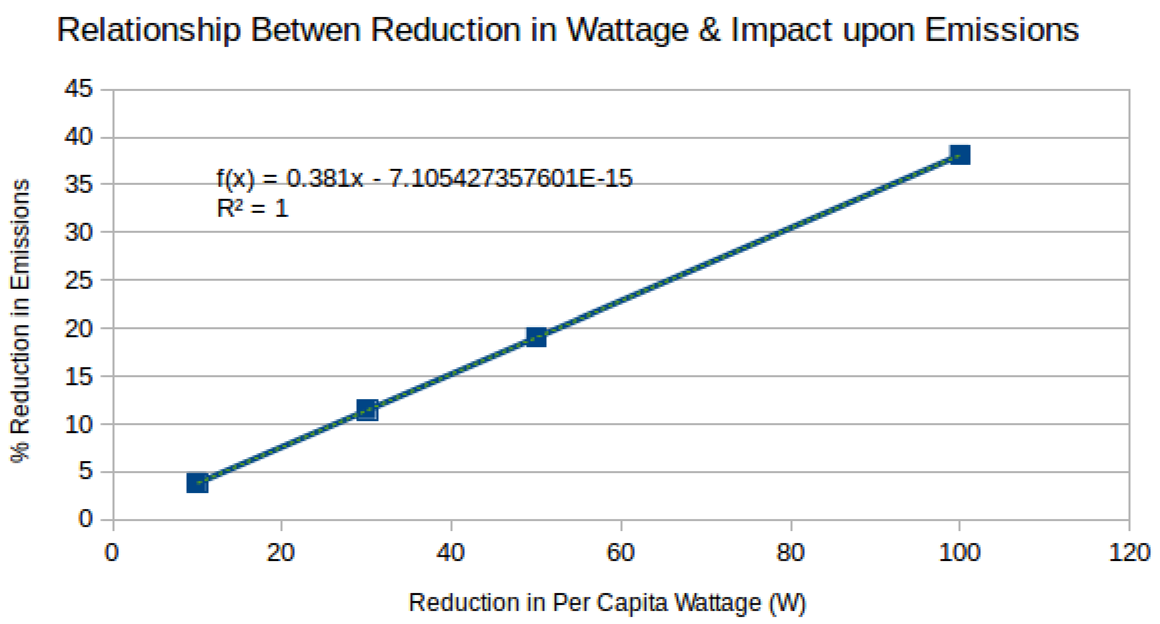


Chart No. 5.5B: Reduction in Wattage & Its Impact upon Emissions

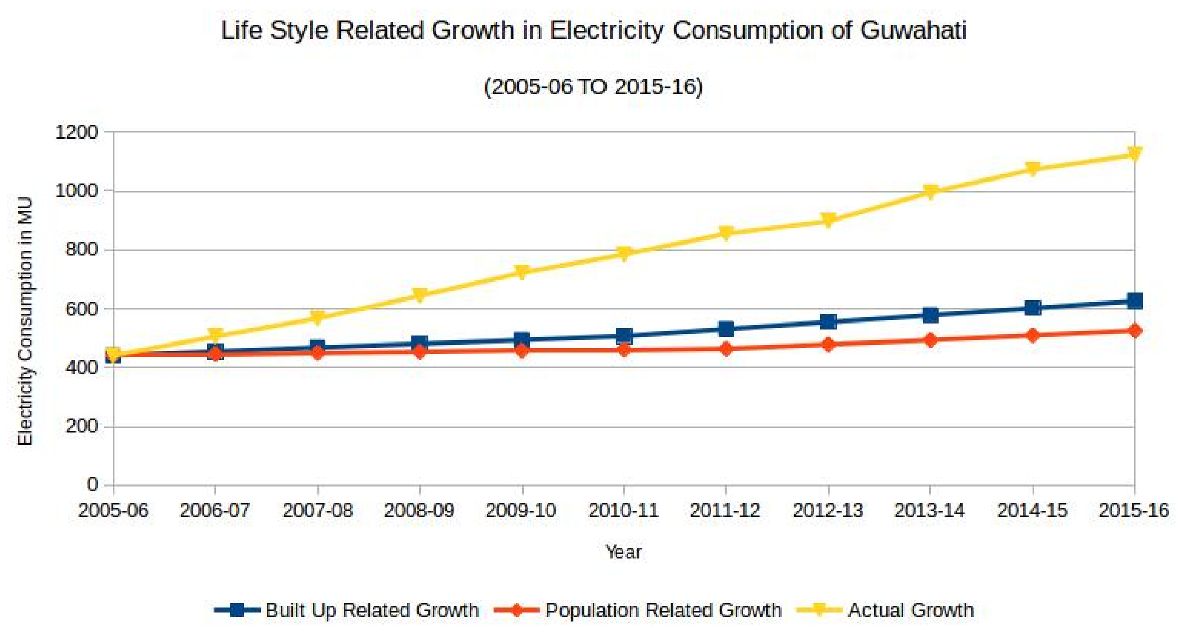


Chart No. 5.6: Growth in Electricity Demand Beyond Population & Built-up Area

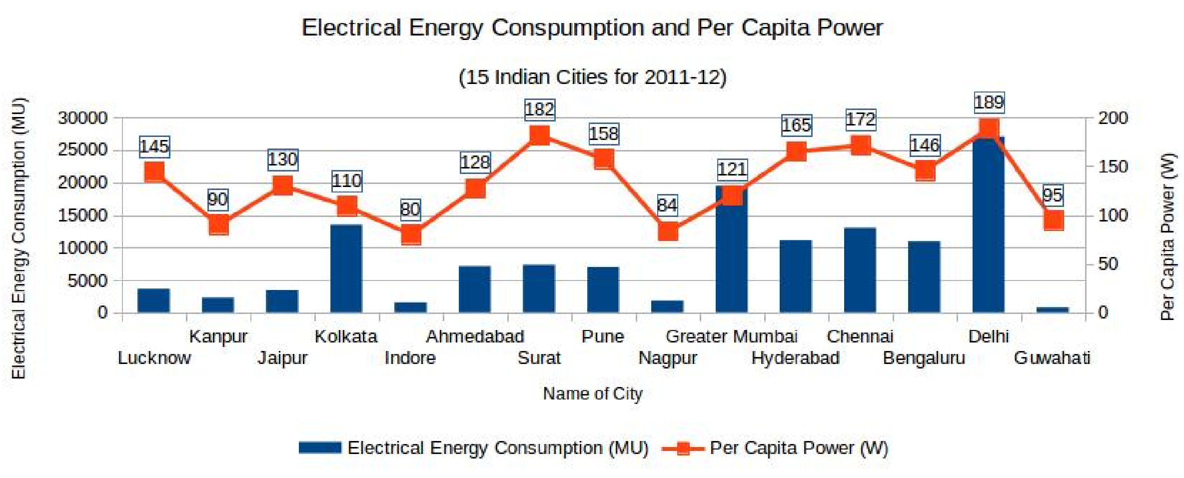


Chart No. 5.7: Electricity Consumption & Per Capita Power for Selected Cities of India

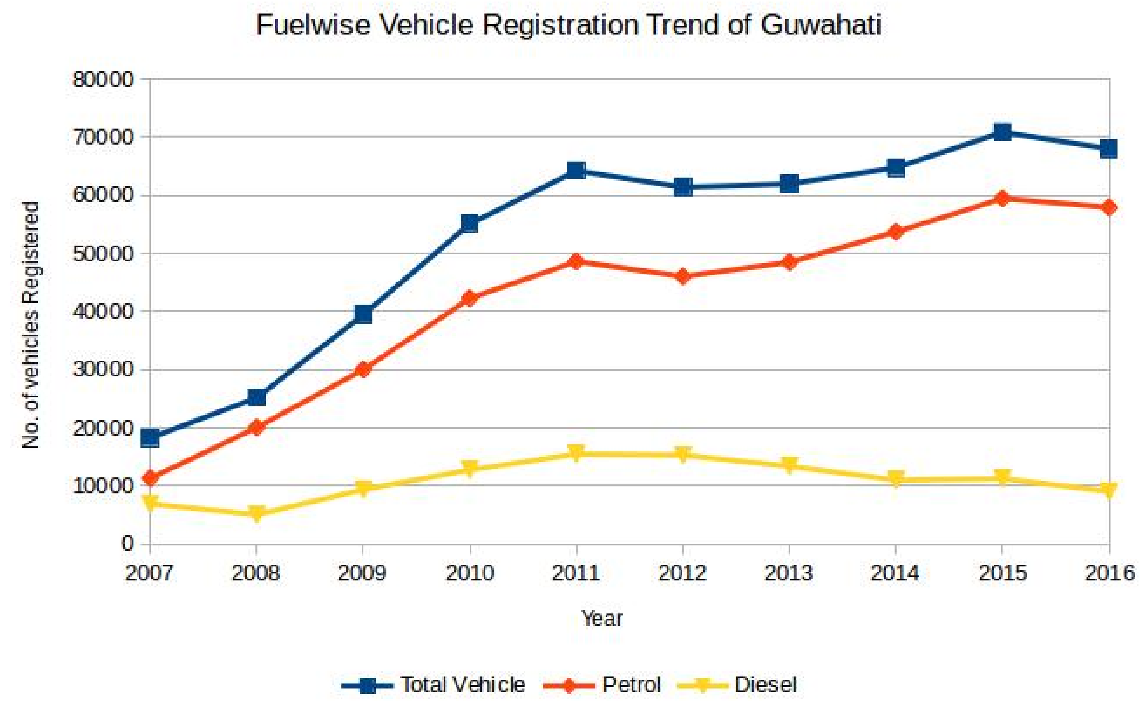


Chart No. 5.8A: Registration of Petrol & Diesel Vehicles in Guwahati (2007-2016)

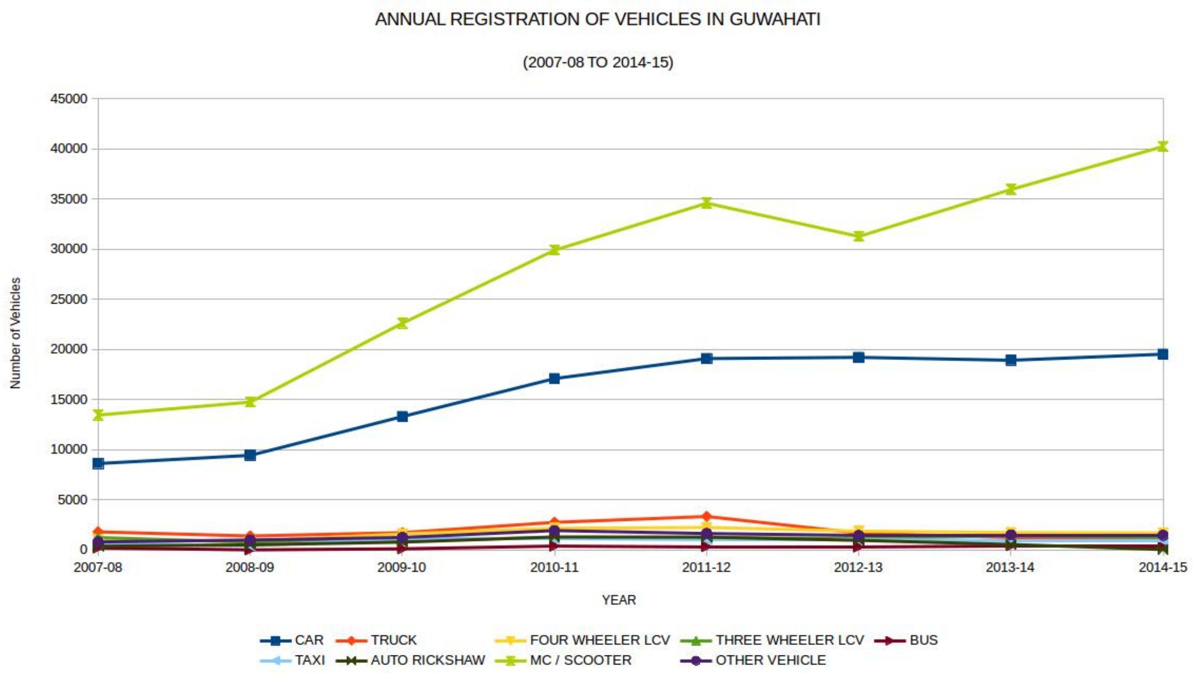


Chart No. 5.8B: Type-wise Break-up of Registered Vehicles of Guwahati

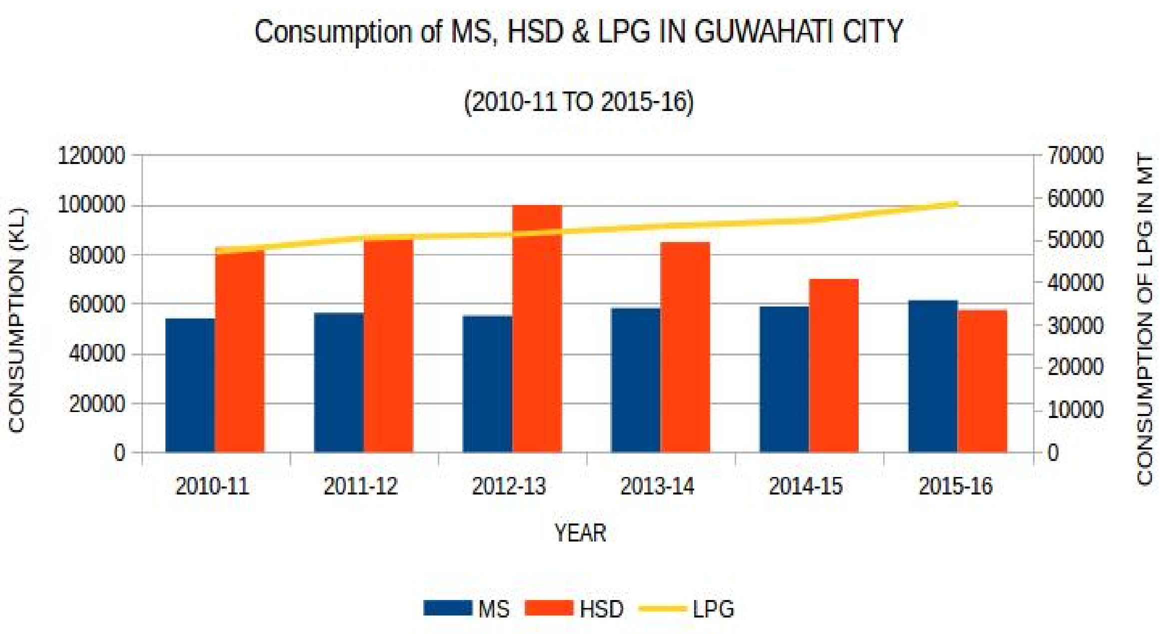


Chart No. 5.9A: Consumption of Petrol, Diesel & LPG in Guwahati

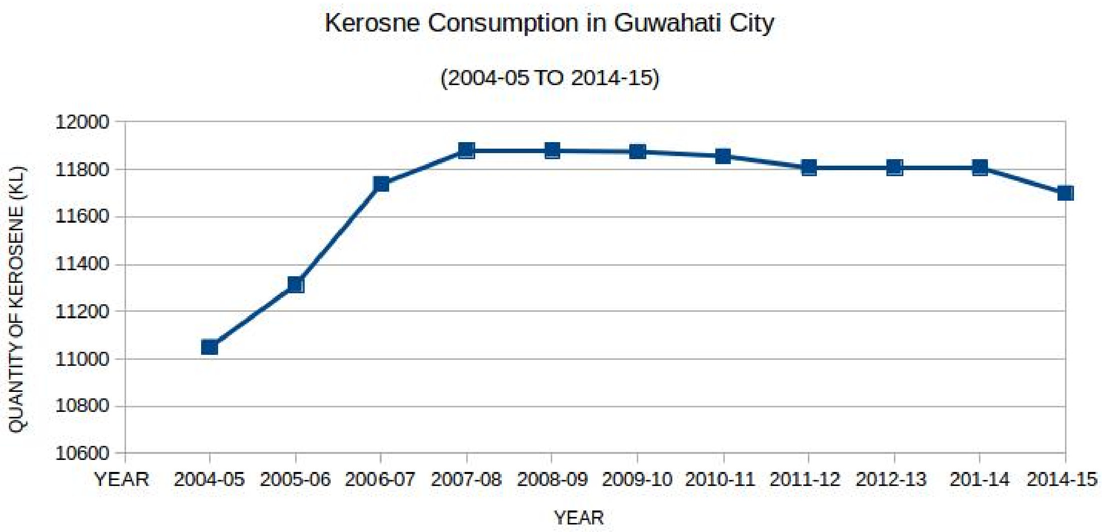


Chart No. 5.9B: Kerosene Consumption of Guwahati City

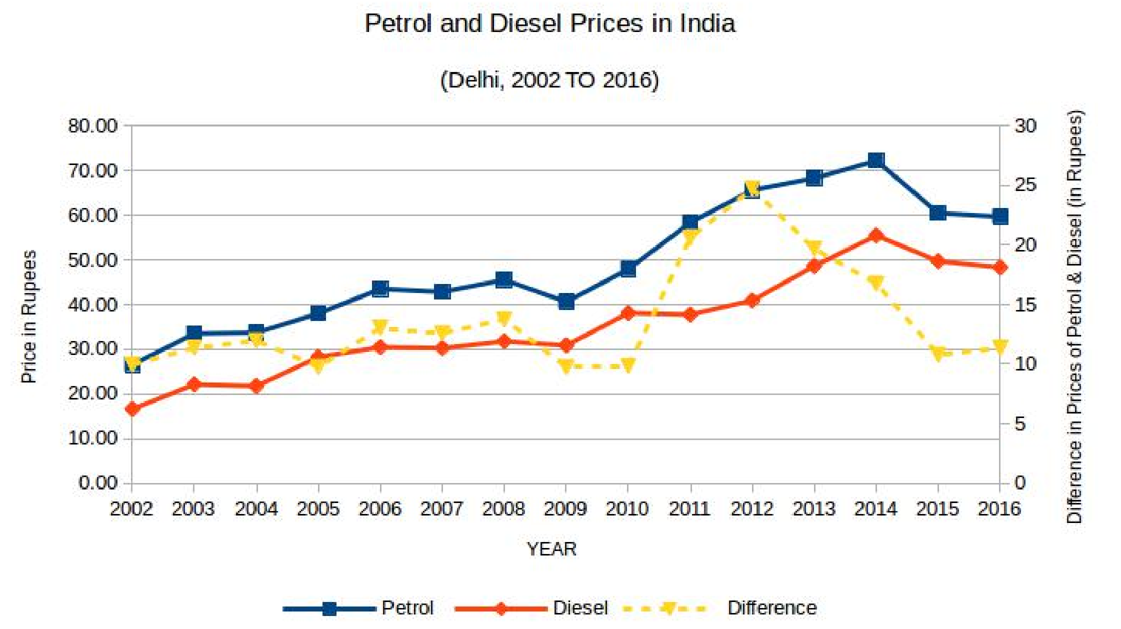


Chart No. 5.9C: Petrol & Diesel Prices (2002-2016)

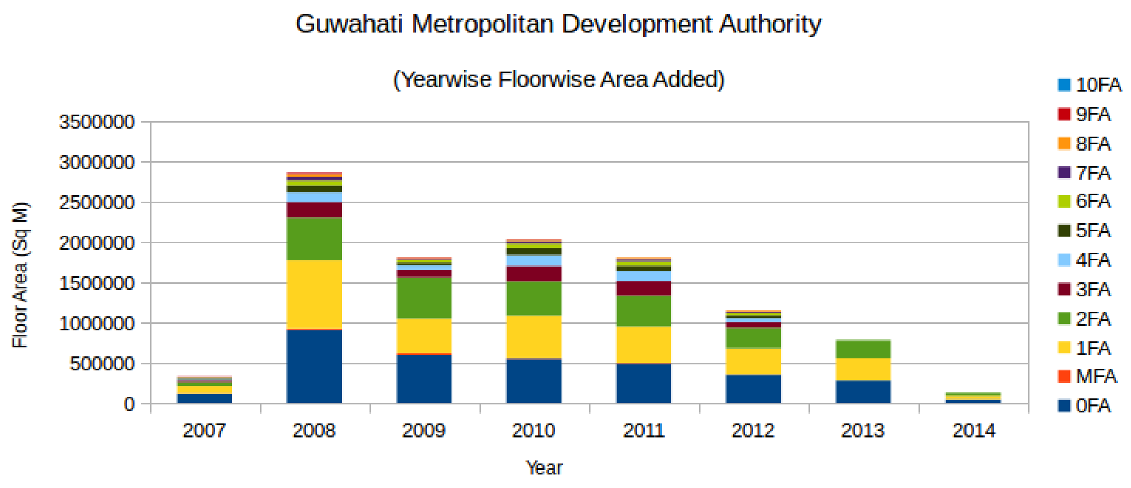


Chart No. 5.10A: Floor Area of Building Permissions Granted by GMDA

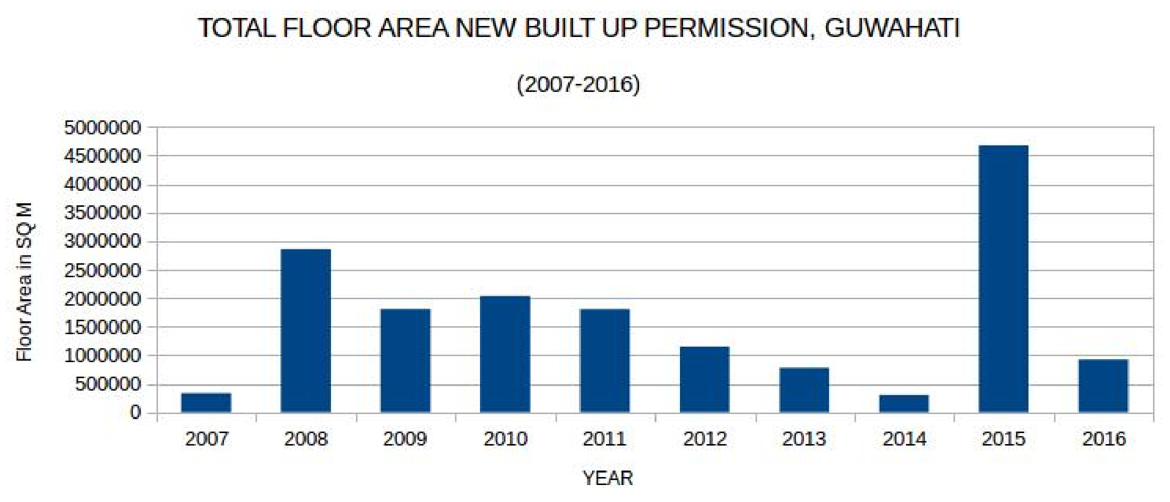


Chart No. 5.10B: Floor Area of Building Permissions by GMDA & GMC

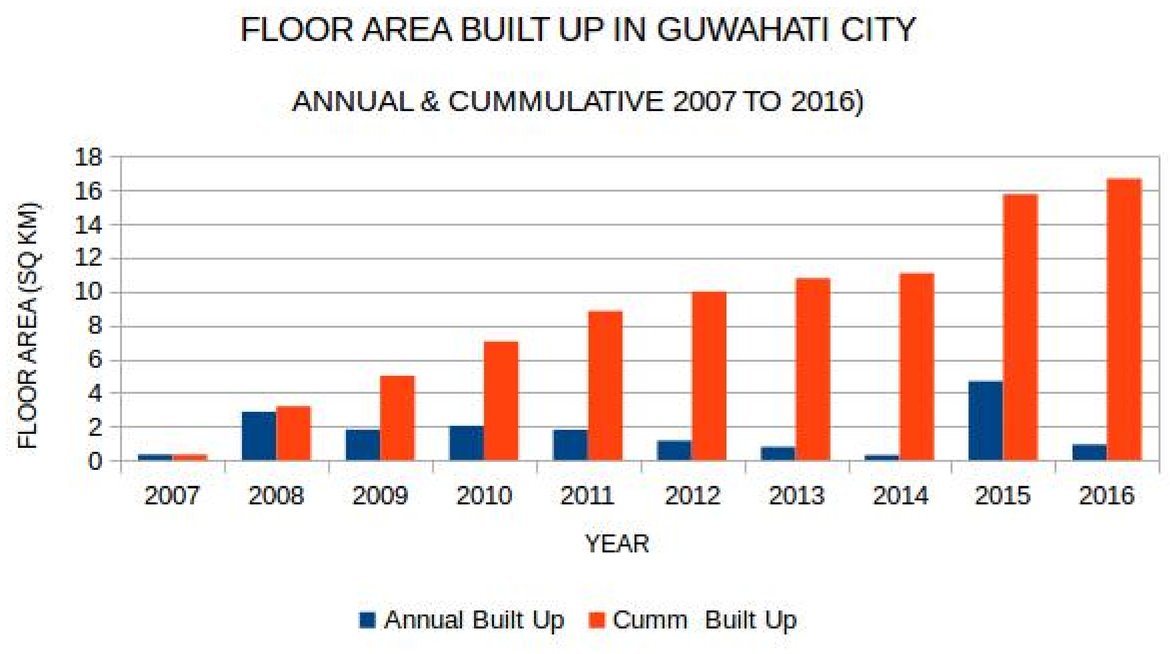


Chart No. 5.10C: Annual & Cumulative Floor Area Built-up

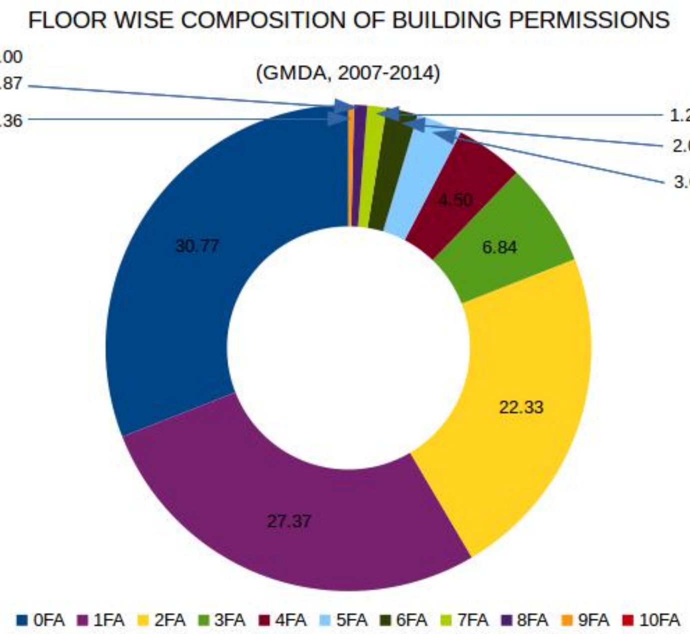


Chart No. 5.10D: Floor wise Composition of Building Permissions by GMDA

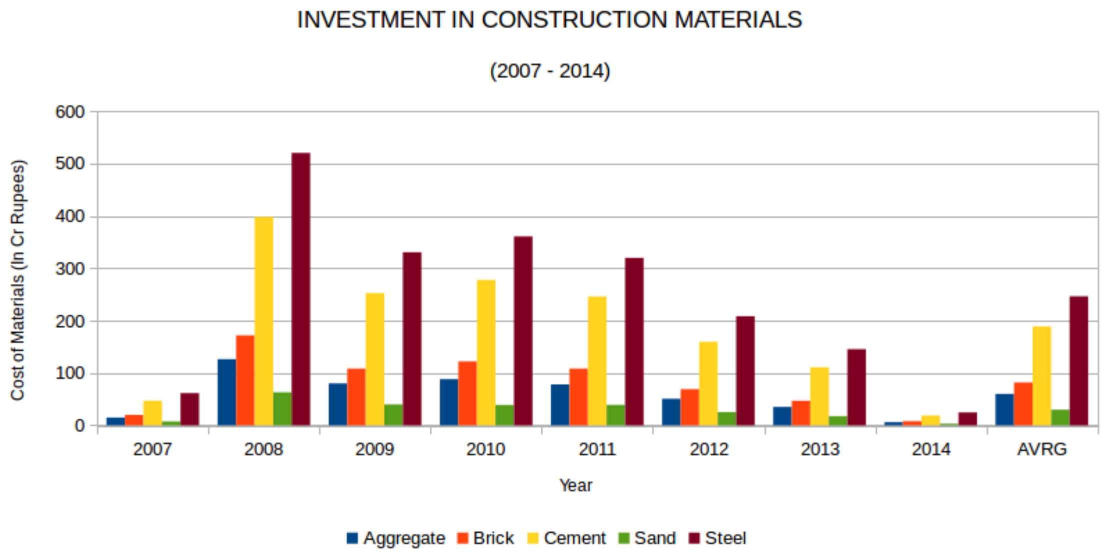


Chart No. 5.10E: Investment in Construction Materials

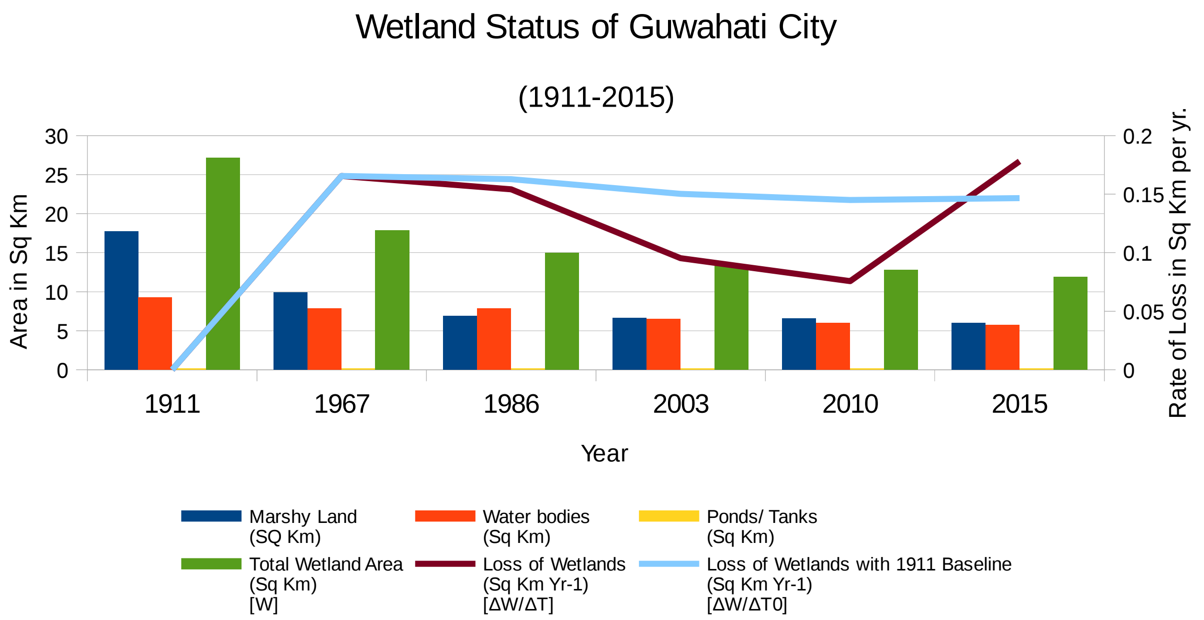


Chart No. 5.11A: Change in Area of Wetlands of Guwahati (1911-2015)

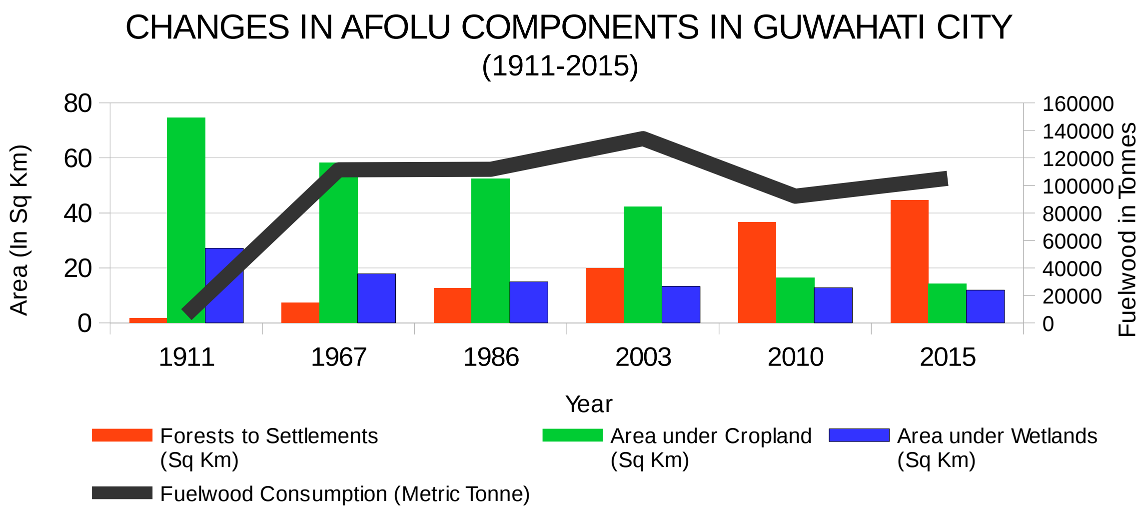


Chart No. 5.11B: Changes in Area of AFOLU Components of Guwahati (1911-2015)

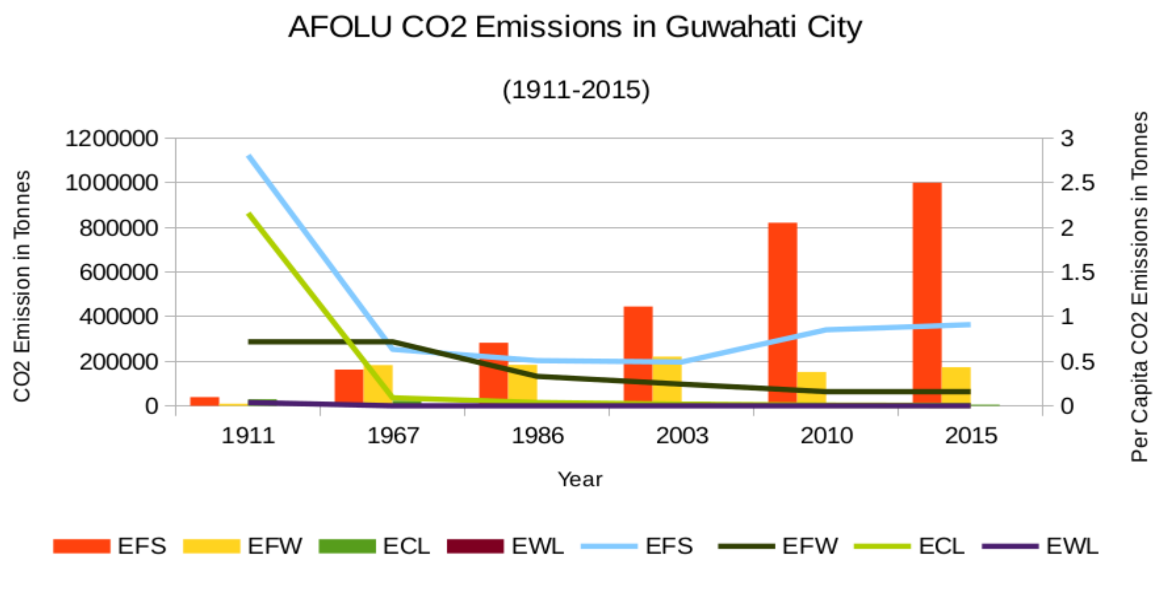


Chart No. 5.11C: Total & Per Capita CO_2 Emissions in AFOLU (1911-2015)

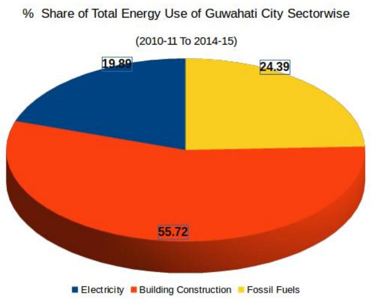


Chart No. 5.12A: Average Share of Total Energy Use (2010-2015)

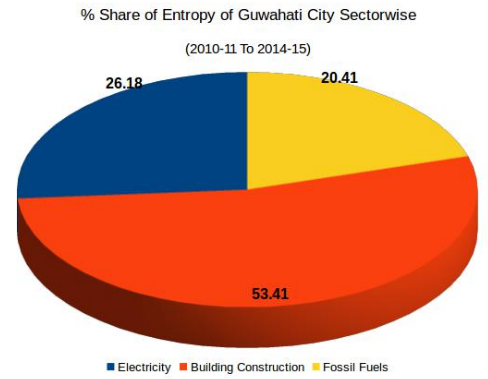


Chart No. 5.12B: Average Share of Entropy (2010-2015)

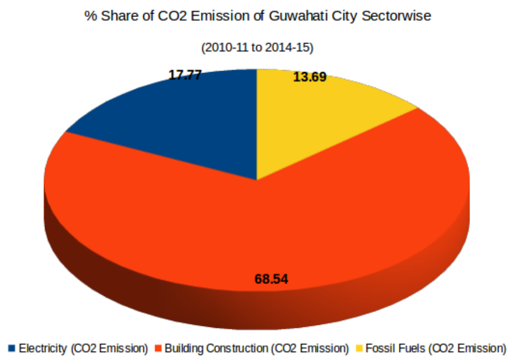


Chart No. 5.12C: Average Share of CO_2 Emission (2010-2015)

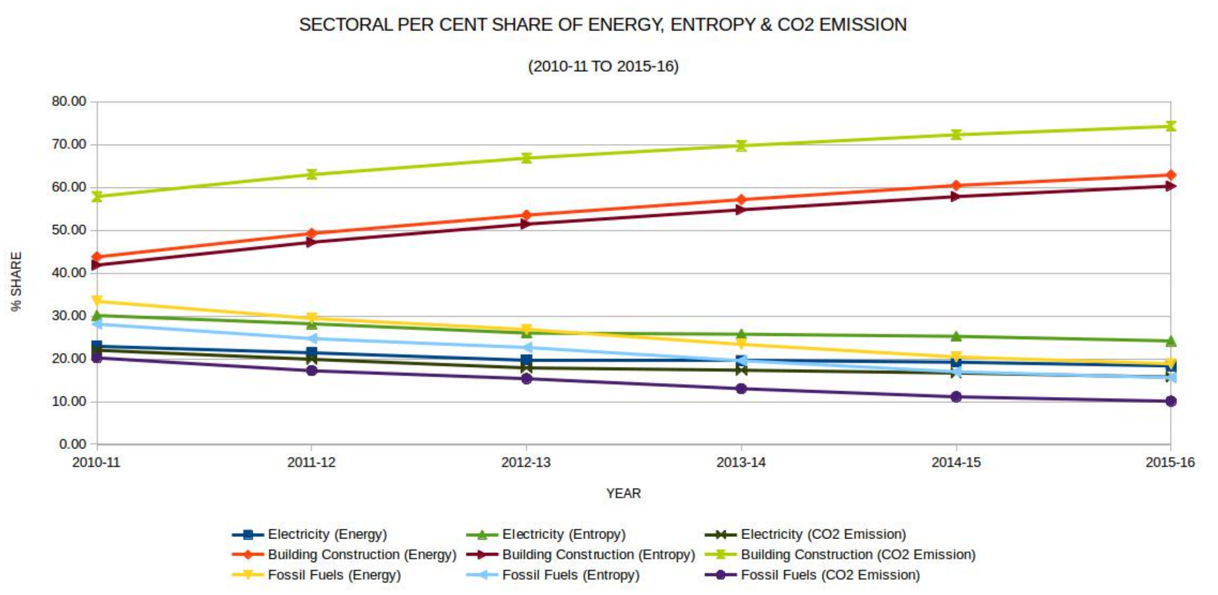


Chart No. 5.12D: Trends in Share of Energy, Entropy & CO_2 Emission Use (2010-2015)

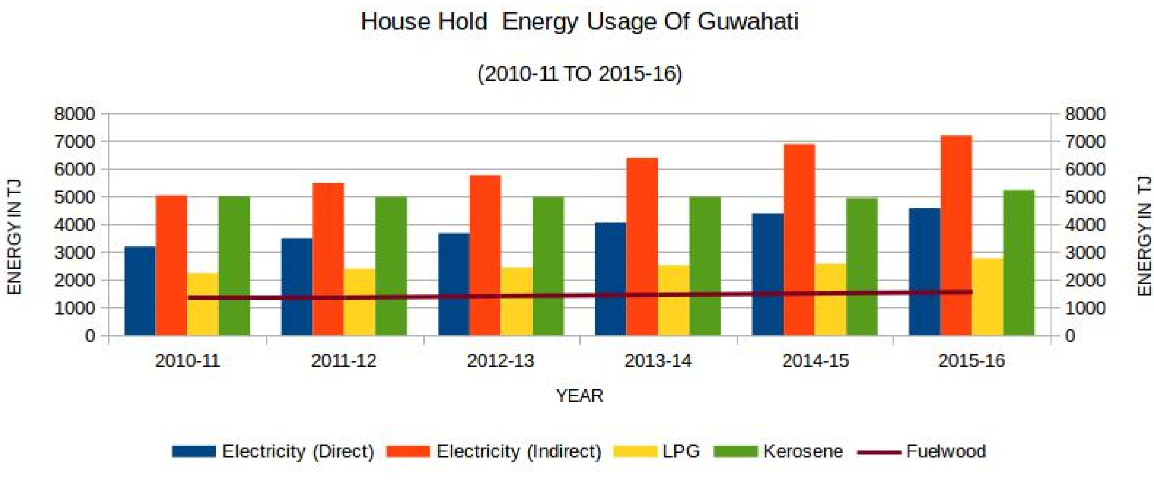


Chart No. 5.12E: Trends in House Hold Energy Usage (2010-2015)

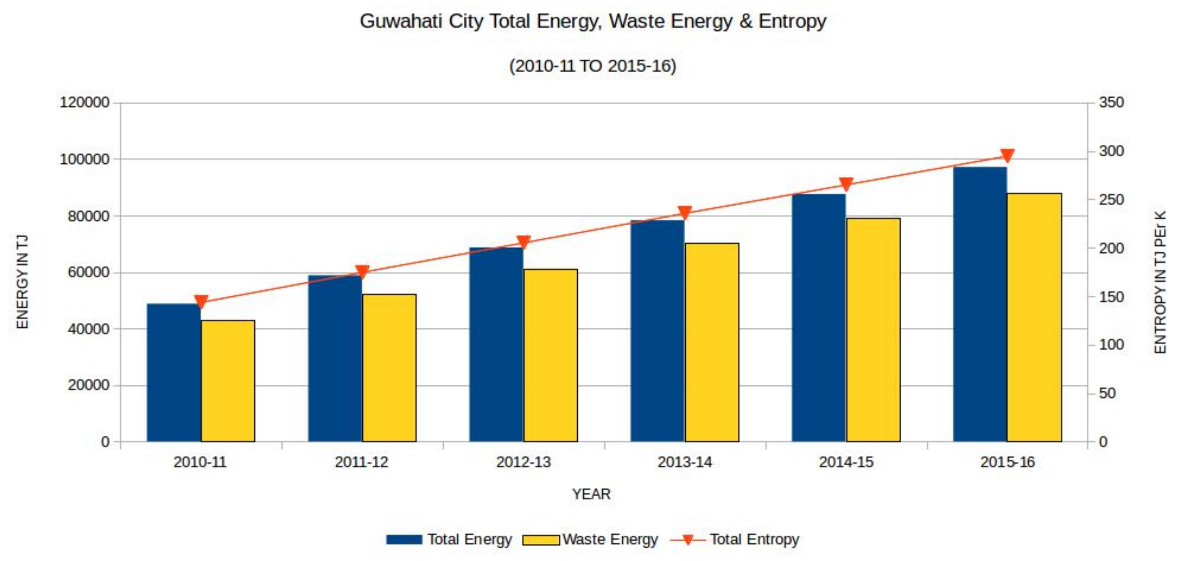


Chart No. 5.12F: Total Energy Usage, Waste Energy & Entropy (2010-2015)

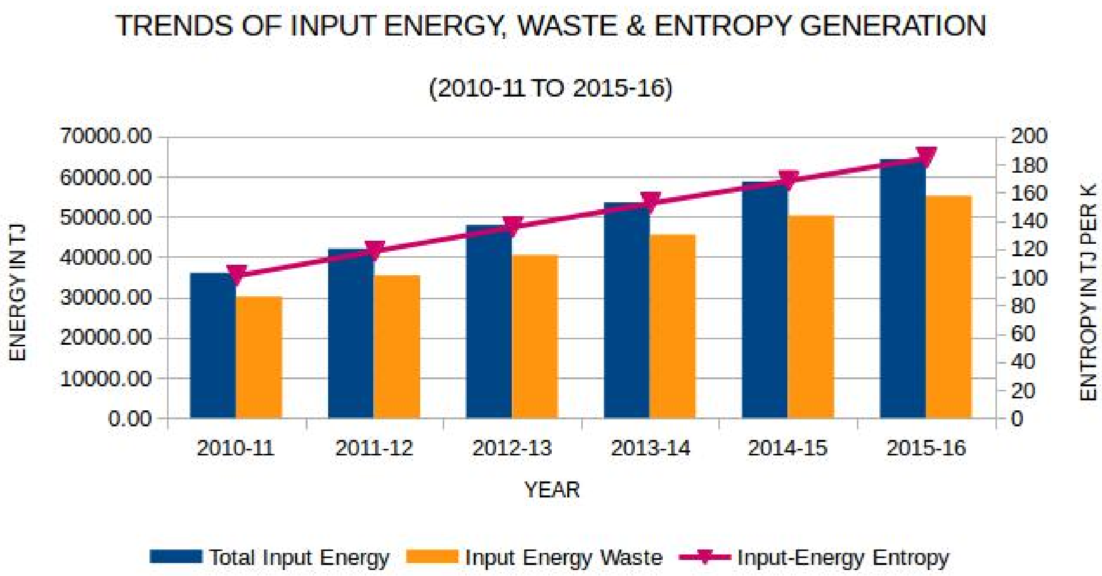


Chart No. 5.12G: Total Direct Energy Usage, Waste Energy & Entropy (2010-2015)

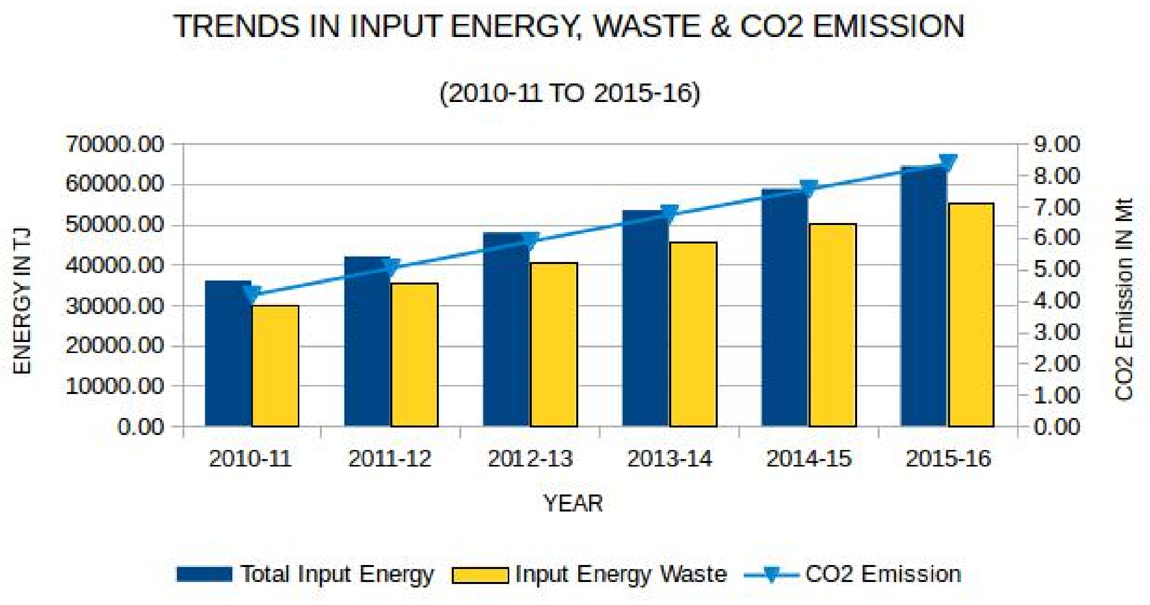
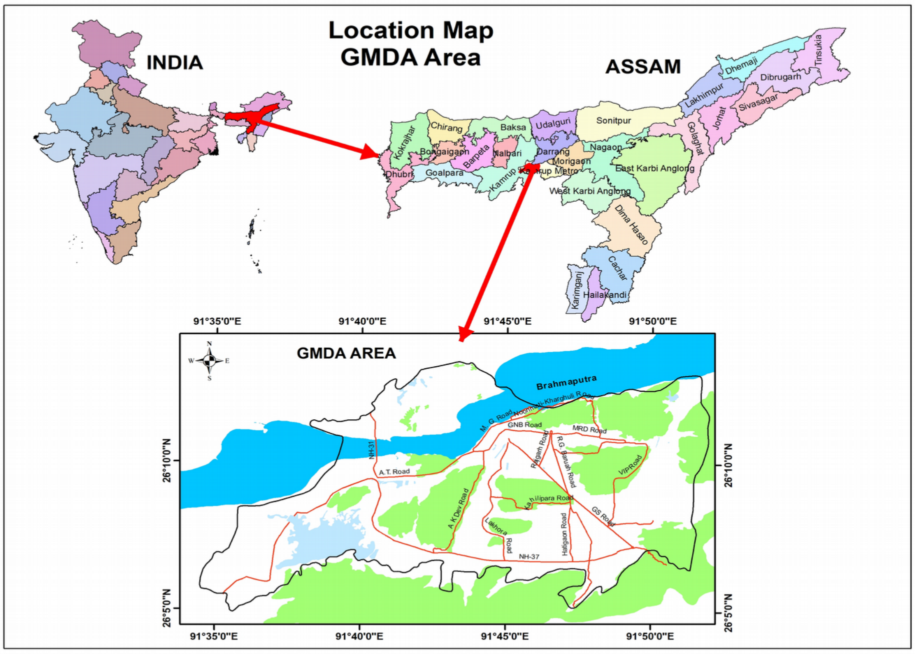
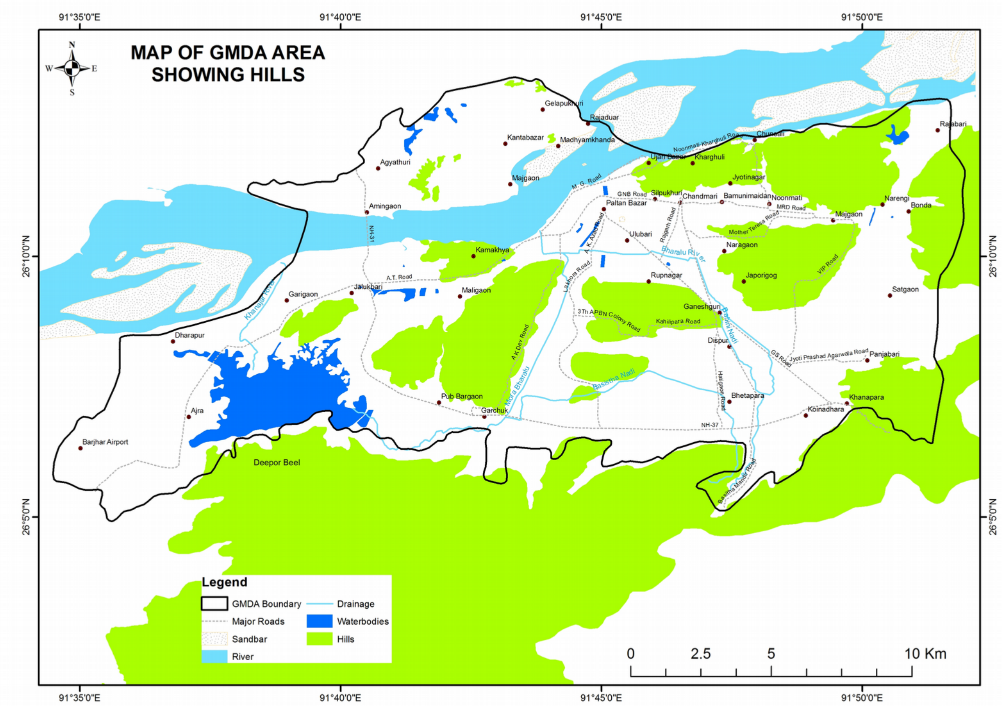


Chart No. 5.12H: Total Direct Energy Usage, Waste Energy &CO_2 Emission (2010-2015)

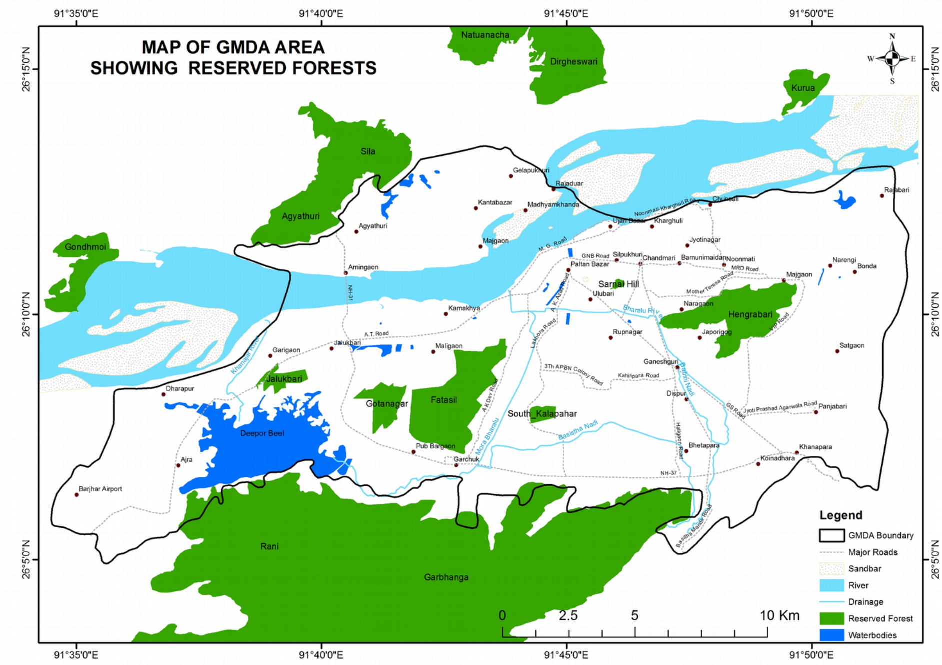
MAPS



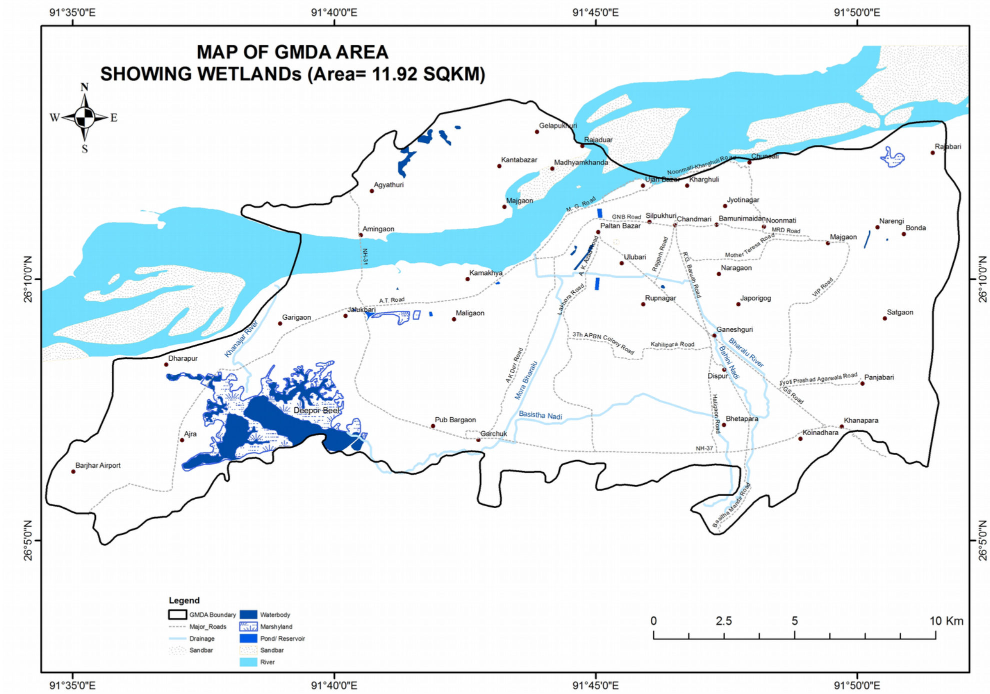
Map No. 5.1: Location Map of Guwahati



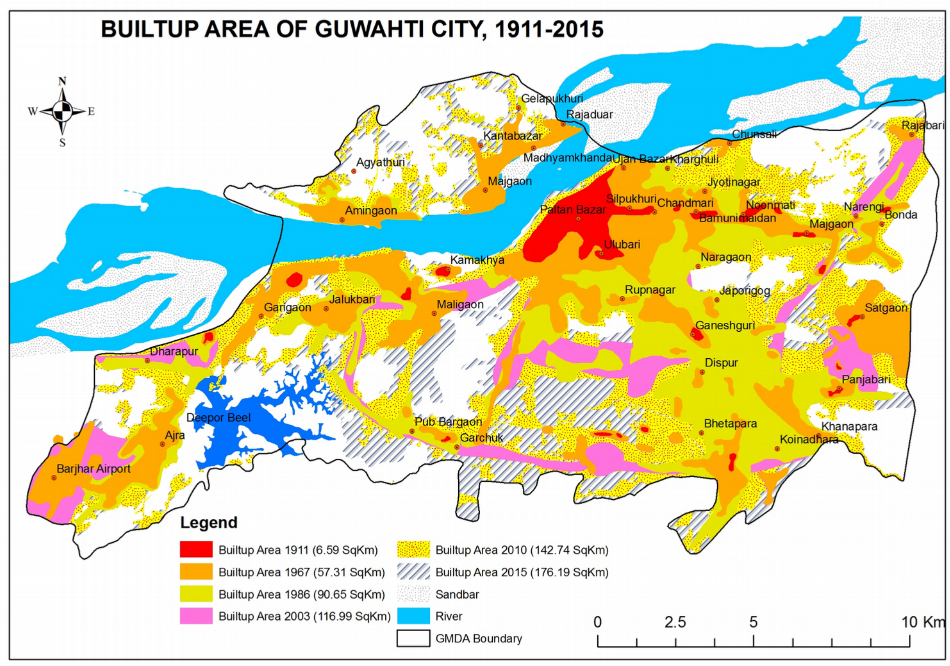
Map No. 5.2: Map of Hills of Guwahati



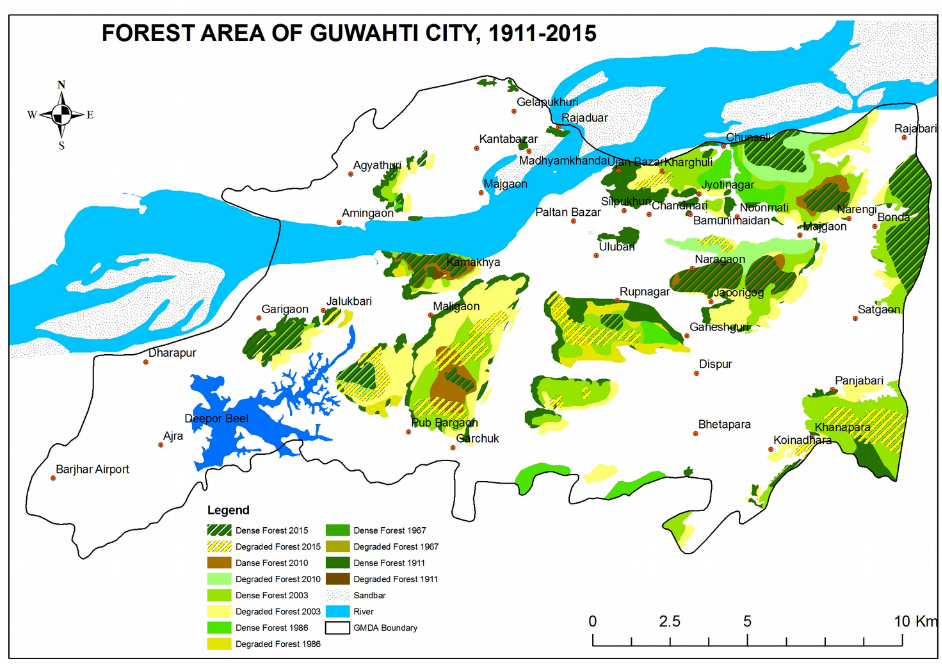
Map No. 5.3: Map of Reserved Forests of Guwahati



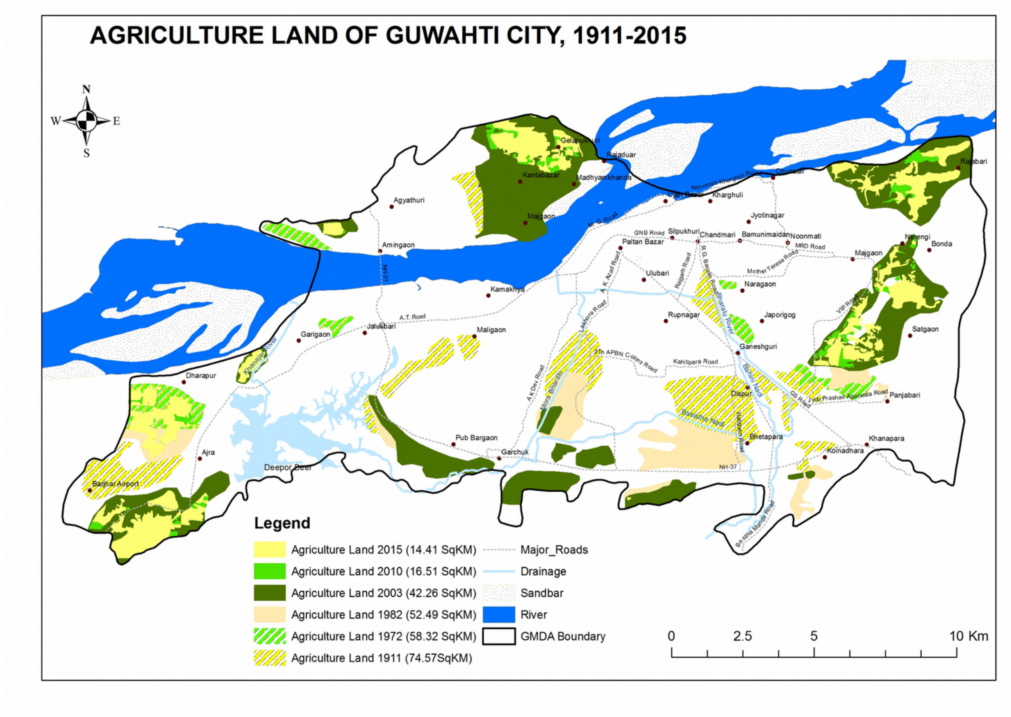
Map No. 5.4: Map of Wetlands of Guwahati



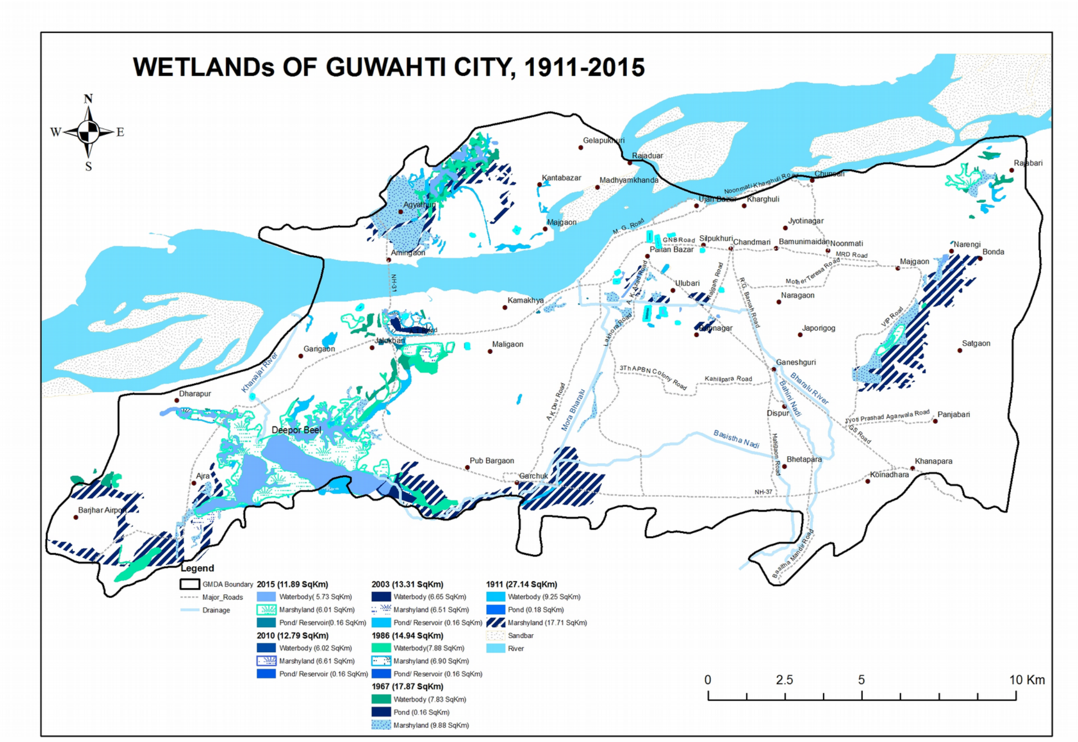
Map No. 5.5: Built Up Growth of Guwahati City



Map No. 5.6: Forest Decline of Guwahati City 1911 to 2015



Map No. 5.7: Agricultural land Status of Guwahati City 1911 to 2015



Map No. 5.8: Wetland Decline of Guwahati City 1911 to 2015