Global Governance of Energy Systems
Transition in a Geopolitical Context - looking at the emerging dynamics of oil and coal beyond the high-income countries

Madhu Madhavi

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

School of Engineering and Innovation
Faculty of Science, Technology, Engineering and Mathematics
The Open University, Milton Keynes, United Kingdom
Declaration

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. The work presented in this thesis is an original contribution and has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification. The following parts of this thesis have been previously peer-reviewed for conferences and publication:


- Madhavi, M. and Nuttall, W.J., 2019. The Future of Clean Coal in India, at The International Conference on Energy and Sustainable Futures (ICESF) 2019, Nottingham, UK

Acknowledgements

I owe a great deal of gratitude to very many people, without whose guidance and support this undertaking could not have been possible. A great deal is owed to:

My supervisors Professor William J Nuttall, Professor Jeff Johnson, Dr Sally Caird from The Open University and Professor John Hatchard from The University of Buckingham for their guidance, supervision and feedback.

My main supervisor Professor Nuttall who closely guided the progress of this work. Thank you for being so welcoming to my ideas and suggestions and for inspiring me to do better. I always looked up to you and benefited immensely from your knowledge and expertise. I also thank you for all the copyediting suggestions on all chapters.

Dr Sally Caird and Professor Jeff Johnson for their continued guidance, writing critique, feedback and encouragement.

Doctoral Training Alliance on Energy and UK Chapter of System Dynamics Society for warmly welcoming me into their communities and extending a platform to share and discuss my work.

To the System Dynamics community at the University of Bergen for painstakingly teaching me System Dynamics modelling skills and for patiently answering all my questions helping debug my models and correcting my formulations. It was a steep learning curve for me, and I could not have done this without you. Professor Nikolaos K Kazantzis for helping me draw my first causal-loop diagram; Christina Gkini, Eduard Romanov and Dr Birgit Kopainsky for helping me debug my models.

My colleagues and friends at the OU: George, Richard, Andy, Yadu, David and Chris. Dona, Olivia and Angela for helping with numerous requests and always being so warm. George for helping out all the way from Grenada. Your models truly inspired me.

I would also like to acknowledge Sri Piyush Goyal, Hon’ble Minister of Coal and Railways for kindly taking time out to meet me during the initial stages of the research and for guiding my knowledge and understanding of India’s policy priorities. Mr Pankaj Batra, Chairman, Central Electricity Authority of India for directing me to correct data sources and for being approachable throughout the process of my research.

I would have given up if it was not for my husband, Kumar, who kept me going in moments of self-doubt.
# Table of Contents

Declaration ........................................................................................................................................... 2  
Acknowledgements .............................................................................................................................. 3  
List of Figures ..................................................................................................................................... 7  
List of Tables ...................................................................................................................................... 8  
Abstract ............................................................................................................................................. 10  
Chapter 1. Introduction ...................................................................................................................... 15  
  Background and Context .................................................................................................................... 20  
  Research framework and questions ..................................................................................................... 25  
  Overarching Research Question for the PhD ..................................................................................... 30  
  Research Sub-Questions and Objectives ............................................................................................. 32  
  Thesis Organisation ............................................................................................................................. 34  
Chapter 2: A mixed-methods approach to the Governance of Energy Systems ............................. 36  
  Overview ........................................................................................................................................... 36  
  Mixed-methods approach .................................................................................................................... 36  
  Document Analysis ............................................................................................................................. 37  
  A Systems Approach to Complex Energy Systems ............................................................................. 39  
  A systems-thinking approach for complex systems in transition ..................................................... 41  
  Systems thinking tools and methods ................................................................................................. 44  
  Energy System Models ....................................................................................................................... 45  
  Evaluating Dynamic Complexity: Agent-Based or System Dynamics Approach? ............................. 49  
  System dynamics for complex energy systems ............................................................................... 53  
  Analysing uncertainty, ambiguity and variability using @Risk ........................................................ 62  
Chapter 3: Global Energy Governance in the 21st Century: Perspectives, Paradigms, Objectives and Architecture .......................................................................................................................... 65  
  Overview ........................................................................................................................................... 65  
  The scholarly origins of governance theory ......................................................................................... 66  
  Governance as structure, process, mechanism and strategy .............................................................. 68  
  Governance Paradigm Shift Theory ................................................................................................... 68  
  Global Energy Governance Theory ................................................................................................... 72  
  Changing Paradigms and Frameworks of Global Energy Governance over the years ..................... 75  
  Global Energy Governance: Objectives and Scope .......................................................................... 85  
  Gaps in the Global Energy Governance Framework ........................................................................ 90  
Chapter 4. A System Dynamics Based Analysis into Global Oil Exchanges and Emerging Dynamics 94  
  Context .............................................................................................................................................. 94  
  System Dynamics and SD Oil Models ................................................................................................. 97
Chapter 8. Summary and Conclusions ................................................................. 204
Answering Questions and Conceptual Implications ........................................ 205
SD Models of Emerging Dynamics of oil and coal ........................................... 209
Future work and final reflections .................................................................. 218
Final Reflections ............................................................................................. 219
Appendix A Model Documentation ............................................................... 221
A1. Documentation for Emerging Oil Dynamics and Global Exchanges model ....................................................... 223
A2. Documentation for Coal in India model .................................................... 230
Bibliography .................................................................................................. 241
List of Figures:

Figure 1.1. Research framework ........................................... 26
Figure 1.2. Venn Diagram mapping the overlaps between this PhD research and other studies .................................................. 27
Figure 1.3. Research approach and methods .................................. 28
Figure 2.1. Use of document analysis for setting the background, context and for carrying out analysis ........................................... 39
Figure 2.2. Energy Modelling Approaches ..................................... 48
Figure 2.3. A simple stock and flow diagram in System Dynamics ............ 58
Figure 2.4. System Dynamics Methodology ..................................... 58
Figure 2.5. General patterns of system behaviour ............................... 59
Figure 2.6. Testing Process for Structural Validity ....................... 60
Figure 4.1. Oil’s Share in global primary energy mix in 2019 .................. 95
Figure 4.2. Crude Oil Prices 1861-2016 Source: [Dudley, 2017] ................ 96
Figure 4.3. Major Oil Trade Movements in 2018 (in million tonnes) .... 102
Figure 4.4. Causal loops diagram showcasing the essential feedbacks in global oil markets and the expected behaviour .................... 107
Figure 4.5. Formal model structure representing the nonlinear global exchanges between the price, supply and demand of oil .......... 107
Figure 4.6. Supply, demand and price equilibrium under controlled conditions generated by the model ....................... 111
Figure 4.7. Simulation results for oil price dynamics responding to specified time lags .................................................. 113
Figure 4.8. SD model demand behaviour in response to a sudden reduction and then restoration of supply in years 20 and 21. Different levels of reduction are analysed (10%, 20% and 30%) .................. 116
Figure 4.9. Oil price in the supply side shortfall shock scenarios presented in figure 4.9 .................................................. 117
Figure 4.10. Total Oil Demand response to China demand reduction .... 121
Figure 5.1. Classification of coal based on its rank .......................... 126
Figure 5.2. Electricity Generation using Coal .................................. 127
Figure 5.3. Steel Production from Coal ......................................... 128
Figure 5.4. Coal Liquid and Gaseous Fuel Products .................... 129
Figure 5.5. Coal transportation between markets ............................. 132
Figure 5.6. Shipping Costs - Baltic Dry Index (2003-2017) .......... 133
Figure 5.7. The Global Coal Trade Map 2014 ............................... 135
Figure 5.8. Coal movements in the Pacific Market in 2015 (Mt) ........ 136
Figure 5.9. Development of coal prices ....................................... 137
Figure 5.10. Coal Prices 2000-2016 ........................................... 142
Figure 5.11. Total Proven Reserves vs. Consumption in 2016 (Mt) .... 147
Figure 6.1. Feedback loop diagram of the problem of unabated CO2 emission from increasing energy demand in India ........... 159
Figure 6.2. Rising CO2 Emissions from India’s Power and Energy Sector .... 159
Figure 6.3. Full Model Structure for India Coal Power Capacity and CO2 Emission Dynamics ........................................... 162
Figure 6.4. Comparison of simulated and historical coal capacity in India .... 164
Figure 6.5. Comparison of simulated and historical Installed Renewable Capacity in India ........................................... 164
Figure 6.6. Comparison of simulated and historical CO2 emissions from India’s Power Sector ........................................... 164
Figure 6.7. Simulated estimates of India’s projected renewable and coal capacities in Reference Scenario .......................... 165
Figure 6.8(a). Simulation result of declining CO2 emissions intensity of India’s GDP ........................................... 166
Figure 6.8(b). Steadily increasing CO2 emissions in the Reference Scenario .......... 166
Figure 6.9. Fraction of coal and renewable capacity in the Reference Scenario .......................... 167
Figure 6.10. Simulation results from India Growth Scenario ............. 167
Figure 6.11. Reduction in emission reduction with the integration of high-efficiency-low-emission coal plant with CCS .......... 169
Figure 7.1. Primary Energy Consumption Matrix in India in 2017 ........ 174
Figure 7.2. Electricity generation from various sources in India 2017 ........................................... 175
Figure 7.3. Liquid-vapour critical point in a Pressure-Temperature phase diagram ........................................... 181
Figure 7.4. The process overview of Integrated Gasification Combined Cycle (with CO2 capture) ........................................... 186
Figure 7.5. Location of Coal Mines and CO2 Storage Potential in India ...... 194
Figure 7.6. COE Graph of Electricity against % reduction in CO2 emissions .................. 199
Figure 7.7. COE distribution profile considering uncertainty in 5 inputs .......................... 200
List of Tables:

<table>
<thead>
<tr>
<th>Table 2.1</th>
<th>Emergence of Energy Systems as Complex Systems</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.2</td>
<td>System Thinking Definition by famous systems thinkers</td>
<td>44</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Review of Literature on Energy System Models</td>
<td>46</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Energy Models Methods and Techniques</td>
<td>47</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Comparison between Agent-based Modelling and System Dynamics</td>
<td>50</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>Partial Comparison of Assumption: Econometrics and System Dynamics</td>
<td>52</td>
</tr>
<tr>
<td>Table 2.7</td>
<td>Some Well-Known System Dynamics Studies in the Oil, Gas and Coal Industry</td>
<td>56</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Meaning and description of Governance</td>
<td>68</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Paradigm Shift Framework</td>
<td>71</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Global Energy Governance Paradigm Change (2000-2020)</td>
<td>83</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>The key goals and scope of Global Energy Governance</td>
<td>86</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Mapping the Global Energy Architecture</td>
<td>89</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Top 10 Crude Oil Producers (in 2020) and Consumers in 2018</td>
<td>101</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>World Coal Trade 2016</td>
<td>134</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Global Market Players in Coal Trade</td>
<td>138</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>Various Coal Price Indices</td>
<td>140</td>
</tr>
<tr>
<td>Table 5.4</td>
<td>An Overview of “Clean Coal” Technologies</td>
<td>145</td>
</tr>
<tr>
<td>Table 6.1</td>
<td>Estimation of Model Boundary</td>
<td>157</td>
</tr>
<tr>
<td>Table 7.1</td>
<td>India’s installed capacity in 2019 by source</td>
<td>177</td>
</tr>
<tr>
<td>Table 7.2</td>
<td>India’s projected macro-indicators</td>
<td>178</td>
</tr>
<tr>
<td>Table 7.3</td>
<td>Typical parameters and specifications of various PC Technologies</td>
<td>181</td>
</tr>
<tr>
<td>Table 7.4</td>
<td>Characteristics of different gasifier types</td>
<td>187</td>
</tr>
<tr>
<td>Table 7.5</td>
<td>Increase in Cost of Electricity with IGCC with and without CO2 capture</td>
<td>189</td>
</tr>
<tr>
<td>Table 7.6</td>
<td>Parameters for determination of electricity cost for FY 2019-24 (CERC, 2019)</td>
<td>197</td>
</tr>
<tr>
<td>Table 7.7</td>
<td>Probability distribution associated with uncertain parameters</td>
<td>198</td>
</tr>
<tr>
<td>Table 7.8</td>
<td>Calculations for electricity cost using various coal-based technologies</td>
<td>198</td>
</tr>
</tbody>
</table>
I dedicate this work to my mother and my husband!
Abstract

Despite efforts to decarbonise energy systems gathering momentum in response to intensified calls demanding tangible action and a departure towards cleaner and net-zero energy pathways, oil and coal dominate the global energy systems and are predicted to remain prominent in the foreseeable future in all energy scenarios, threatening the transition to net-zero pathways. Even as the consumption of fossil fuels, particularly coal-fired power declines in the West, India’s continued use of coal, under the current trends, is likely to be one of the dominant contributors towards the global increase in CO$_2$ emissions in 2040. Oil will also continue to remain strategically important to the global energy systems in the near-term scenario and will continue to influence energy markets and global geopolitics. These realities, together, present grave prospects for the world’s environment.

Global energy governance processes have a key role to play but a fundamentally different approach will be needed to lead energy systems decarbonisation. Recognizing the importance for holistic insights for successful and effective governance in the context of net-zero transition and the emerging geopolitics of oil and coal, a mixed-methods approach is adopted in this thesis to analyse the potential of global energy governance arrangements for leading the net-zero transition. The use of both quantitative and qualitative methods enables to capture diverse perspectives to explore the key relationships and feedbacks critical for future energy system transition. Document analysis helps to explore the relevant theories, concepts, and trends. This thesis is informed empirically by system-dynamics models exploring scenarios emerging from continued oil price volatility and expansion of coal-fired generation within the context of energy systems transition.

The oil model tests the scenarios resulting from supply-side shocks linked to energy security and demand disruptions as a possible consequence of growing pressures of decarbonisation. Damped oscillation in oil prices occur resulting from ongoing readjustments in systems, occurring even long after initial shocks have passed. Without strategic intervention through effective governance arrangements, the world may remain locked-into using oil in the foreseeable future. Global governance institutions can use the low-price window, to help oil producers to diversify their economies and initiate structural reform to gradually steer the world away from oil. Results from India coal SD-model show that even as India succeeds in meeting its Paris commitment of reducing the emission intensity of its GDP by 30-35% below 2005 levels by 2030, the CO$_2$ emissions will continue to rise and can only be stabilised with the use of advanced clean coal technology enabled with capture. The insights from India-coal SD model tested by performing a techno-economic feasibility analysis using both document analysis and Monte Carlo Simulation using @RISK software, reveal that notwithstanding their technological suitability, advanced clean coal technologies enabled with CCS will significantly increase the cost of electricity and struggle in India, as in other emerging economies, without adequate financial support, knowledge transfer and international cooperation. Analysed against the challenges revealed by the scenarios examined by the oil and coal model, this thesis observes that the existing institutional framework lacks the mandate to effectively deal with the complexity of challenges facing energy systems transition towards secure, sustainable and affordable energy pathways. This thesis argues that despite some recent claims that a new era for energy governance is underway, its institutional landscape and capacity has remained largely unchanged over the past few decades and, in its current form, is rendered ineffective, in addressing the emerging challenges of decarbonisation. A multi-actor, multi-regime complex of actors with proper mandate and remit may be effective. The research recommends that closer coordination and cooperation between processes and frameworks engaged in governance of energy systems will be needed to address contemporary energy challenges.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADB</td>
<td>Asian Development Bank</td>
</tr>
<tr>
<td>APL</td>
<td>Above Poverty Line</td>
</tr>
<tr>
<td>APP</td>
<td>The Asia-Pacific Partnership</td>
</tr>
<tr>
<td>ASEAN</td>
<td>Association of Southeast Asian Nations</td>
</tr>
<tr>
<td>ASU</td>
<td>Air Separation Unit</td>
</tr>
<tr>
<td>BHEL</td>
<td>Bharat Heavy Electricals Limited</td>
</tr>
<tr>
<td>BP</td>
<td>British Petroleum</td>
</tr>
<tr>
<td>BPL</td>
<td>Below Poverty Line</td>
</tr>
<tr>
<td>BT</td>
<td>Billion Tonne</td>
</tr>
<tr>
<td>BTU</td>
<td>British Thermal Unit</td>
</tr>
<tr>
<td>CAGR</td>
<td>Compound Annual Growth Rate</td>
</tr>
<tr>
<td>CBM</td>
<td>Coal Bed Methane</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CCT</td>
<td>Clean Coal Technologies</td>
</tr>
<tr>
<td>CCUS</td>
<td>Carbon Capture Utilisation and Sequestration technologies</td>
</tr>
<tr>
<td>CEA</td>
<td>Central Electricity Authority</td>
</tr>
<tr>
<td>CERC</td>
<td>Central Electricity Regulatory Commission</td>
</tr>
<tr>
<td>CFB</td>
<td>Circulating Fluidised Bed Combustion</td>
</tr>
<tr>
<td>CIL</td>
<td>Coal India Limited</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>COP</td>
<td>Conference of the Parties</td>
</tr>
<tr>
<td>COP21</td>
<td>Conference of the Parties in Paris</td>
</tr>
<tr>
<td>DTA</td>
<td>Doctoral Training Alliance (Energy)</td>
</tr>
<tr>
<td>ECBM</td>
<td>Enhanced Coalbed Methane Recovery</td>
</tr>
<tr>
<td>ECT</td>
<td>Energy Charter Treaty</td>
</tr>
<tr>
<td>EFOM</td>
<td>Energy Flow Optimisation Model</td>
</tr>
<tr>
<td>EGEAS</td>
<td>Electricity Generation Expansion Analysis System</td>
</tr>
<tr>
<td>EITI</td>
<td>Extractive Industries Transparency Initiative</td>
</tr>
<tr>
<td>EOR</td>
<td>Enhanced Oil Recovery</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>ESPs</td>
<td>Electrostatic Precipitators</td>
</tr>
<tr>
<td>FBC</td>
<td>Fluidised Bed Combustion</td>
</tr>
<tr>
<td>FCC</td>
<td>ASEAN Regional Knowledge Network on Forests and Climate Change</td>
</tr>
<tr>
<td>FF</td>
<td>Fabric-Filters</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue Gas Desulphurisation</td>
</tr>
<tr>
<td>FLEG</td>
<td>ASEAN Regional Knowledge Network on Forest Law Enforcement and Governance</td>
</tr>
<tr>
<td>FREE</td>
<td>Feedback-Rich Energy Economy model</td>
</tr>
<tr>
<td>G20</td>
<td>Group of Twenty</td>
</tr>
<tr>
<td>G8</td>
<td>Group of Eight</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>GOM</td>
<td>Global Oil Model</td>
</tr>
<tr>
<td>GT</td>
<td>Gigatonne</td>
</tr>
<tr>
<td>GW</td>
<td>Gigawatts</td>
</tr>
<tr>
<td>HDI</td>
<td>Human Development Index</td>
</tr>
<tr>
<td>HEL</td>
<td>Heavy Electricals Limited</td>
</tr>
<tr>
<td>HELE</td>
<td>High Efficiency Low Emission</td>
</tr>
<tr>
<td>HPBP</td>
<td>High Pressure Boiler Plant</td>
</tr>
<tr>
<td>HPEL</td>
<td>Heavy Power Equipment Limited</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>IDEAS</td>
<td>Improved Dynamic Energy Analysis Simulation</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IEF</td>
<td>International Energy Forum</td>
</tr>
<tr>
<td>IGCC</td>
<td>Integrated Gasification Combined Cycle</td>
</tr>
<tr>
<td>IMF</td>
<td>International Monetary Fund</td>
</tr>
<tr>
<td>INDC</td>
<td>India’s Intended Nationally Determined Contribution</td>
</tr>
<tr>
<td>IPE model</td>
<td>International Petroleum Exchange model</td>
</tr>
<tr>
<td>IPEEC</td>
<td>International Partnership for Energy Efficiency Cooperation</td>
</tr>
<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
</tr>
<tr>
<td>LEAP</td>
<td>Long-range Energy Alternative Planning</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MARKAL</td>
<td>Market Allocation Model</td>
</tr>
<tr>
<td>MEA</td>
<td>Mono-ethanolamine</td>
</tr>
<tr>
<td>MEM</td>
<td>Major Economies Meetings</td>
</tr>
<tr>
<td>MTCE</td>
<td>Million Tonne of Coal Equivalent</td>
</tr>
<tr>
<td>MTOE</td>
<td>Million Tonne of Oil Equivalent</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatts</td>
</tr>
<tr>
<td>NEMS</td>
<td>National Energy Modelling System</td>
</tr>
<tr>
<td>NEP</td>
<td>National Energy Policy of India</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-Governmental Organisation</td>
</tr>
<tr>
<td>NHPC</td>
<td>National Hydro Power Corporation</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>Nitrogen Oxide</td>
</tr>
<tr>
<td>NPCIL</td>
<td>Nuclear Power Corporation of India Limited</td>
</tr>
<tr>
<td>NTPC</td>
<td>National Thermal Power Corporation</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
</tr>
<tr>
<td>PC</td>
<td>Pulverised Coal</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>POLES</td>
<td>Prospective Outlook on Long-term Energy Systems</td>
</tr>
<tr>
<td>PPP</td>
<td>Purchasing Power Parity</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>REEEP</td>
<td>Renewable Energy and Energy Efficiency Partnership</td>
</tr>
<tr>
<td>SC</td>
<td>Supercritical</td>
</tr>
<tr>
<td>SCCL</td>
<td>Singareni Collieries Company Limited</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>SD</td>
<td>System Dynamics</td>
</tr>
<tr>
<td>SEBs</td>
<td>States Electricity Boards</td>
</tr>
<tr>
<td>SNCR</td>
<td>Selective Non-Catalytic Reduction</td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>Sulphur Dioxide</td>
</tr>
<tr>
<td>SO\textsubscript{x}</td>
<td>Sulphur Oxide</td>
</tr>
<tr>
<td>TOE</td>
<td>Tonne of Oil Equivalent</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>TPES</td>
<td>Total Primary Energy Supply</td>
</tr>
<tr>
<td>TPP</td>
<td>Thermal Power Plants</td>
</tr>
<tr>
<td>T&amp;D</td>
<td>Transmission and Distribution</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>USC</td>
<td>Ultra-Supercritical</td>
</tr>
<tr>
<td>USDOE</td>
<td>United States Department of Energy</td>
</tr>
<tr>
<td>WASP</td>
<td>Water Quality Analysis Simulation Program</td>
</tr>
<tr>
<td>WEM</td>
<td>World Energy Model</td>
</tr>
</tbody>
</table>
Chapter 1. Introduction

Energy is a fundamental requirement for any society’s growth and development. It is, in Schumacher’s words, “not just another commodity, but the precondition of all commodities” (Schumacher, 1977). The need to secure its supply, in the most affordable, reliable, and sustainable manner possible, underscores some of the key policy priorities globally. Energy is also at the centre of some of the toughest global challenges as energy systems, including patterns of production, distribution and storage, and end-use application, evolve across its entire value chain with emerging geopolitics of energy, a rapidly changing political and technological landscape and in response to the problems of the energy trilemma. In the meanwhile, current energy systems are dominated by fossil fuels which create wide-ranging externalities with deep social costs. An IRENA study estimates the external effects of energy supply and use related to climate change and air pollution to be in the order of USD 2.2 trillion – USD 5.9 trillion per year (IRENA, 2016).

Energy systems transition and the response to the problems of the energy trilemma is undeniably among the defining issues of the 21st century. The urgent need to transit to cleaner energy net-zero pathways by 2050 to limit the global temperature increase to no more than 1.5°C dominate the energy policy agenda and public debate (UNFCCC, 2016). With the impacts of climate change becoming increasingly visible across the world, discussion on the immediacy and urgency of climate actions have intensified. There is also a wider recognition that concerted efforts globally are needed to deal with the impending climate crisis. Despite this wide consensus mandating globally convergent efforts to deal with energy externalities, energy policies are restricted by local realities. Glaring discrepancies between the prevalent policy trajectories currently exist in different parts of the world creating significant barriers to effective transition and energy systems objectives.

The inherent local context and interdependencies that arise because of local social, economic and political realities in countries often drive the policy agenda locally, and can, in the absence of a coherent and binding mandate, potentially delink the locally pursued and globally desired policy goals and roadmap. This becomes apparent with the forecasted growth in the share of coal and oil in the global energy mix to meet energy demand growth driven by increasing prosperity and living standards in the emerging world (BP, 2020; IEA, 2020). Over the next several decades, as developing countries, led by China and India, emerge as the biggest consumers of energy, new paradigms with far-reaching consequences for energy demand and supply will emerge (Jordan, et al., 2018).
Given the correlation between energy use and Human Development Index (HDI)\(^1\), it can be assumed with some certainty, that with growth and development in developing countries, like India, their energy consumption per capita will increase significantly. Energy access will also be crucial to their efforts for ending poverty and boosting shared prosperity. Despite pathbreaking achievements in the recent past, providing access to modern forms of energy and creating clean lighting and cooking environment for a very large number of people around the world has not yet been possible. More than 800 million people, mostly in developing countries, continue to live without access to electricity and nearly 3 billion people rely on traditional biomass for cooking and heating, resulting in indoor and outdoor pollution with widespread, and in some cases even fatal, health impacts (WorldBank, 2019).

There, however, is evidence that the structure of energy demand and supply has started to change globally over the past two decades with increasing deployment of renewable energy and a conscious shift to cleaner fuel sources, and there are reasons to be cautiously optimistic that these will speedily and eventually displace fossil fuels in many parts of the world (BP, 2020). However, in many other parts, fossil fuels will remain a dominant part of the energy mix in the foreseeable future.

At a time when the consumption of fossil fuels, particularly coal-fired power is declining in the West, accelerated by phase-out commitments and the rise of renewables, it increases in many developing countries, particularly India, to meet the rapidly rising demand for electricity, driven by population growth and improvements in living standards. Studies suggest that even with the expected growth in renewable energy, coal will remain the dominant fuel for electricity generation in India (BrookingsInstitutions, 2019). Despite the rapidly falling cost of renewable energy generation in recent years, comparing the cost of new renewable generation to the existing coal-fired generation, the economics currently favour coal (ibid). Coal today accounts for 37% of electricity generation worldwide and about 30% of global CO\(_2\) emissions; currently the world’s largest single source of energy, coal is set to generate 22% of the world’s electricity in 2040 (IEA, 2020). India’s continued use of coal, under the current trends, is likely to be one of the dominant contributors towards the global increase in CO\(_2\) emissions in 2040 (IEA, 2020; 2021). BP estimates that driven primarily by the need for oil use in the petrochemical industry, the consumption of liquid fuels remains at around 100 million barrels/day for the next twenty years (BP, 2021). According to IEA estimates, oil prices during this period will follow a downward trajectory, falling from the current level of $75 to about

---

\(1\) The Human Development Index (HDI) is the geometric mean of normalised indices of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. (UNDP, 2018)
$35 a barrel by 2030 and then further down to $25 a barrel by 2050 (IEA, 2021). The low oil prices, on the other hand, can increase their consumption in developing countries.

The ease and economics of resource availability will continue to determine their viability of adoption and integration, particularly when these choices compete with other overriding objectives and priorities. More targeted efforts to develop and expand indigenous energy resources will also be undertaken, to reduce dependency on imported sources and as a safeguard against increasing geopolitical and price instabilities. Nation-states and their governments, in assessing the suitability of the available options, will be guided by and increasingly rely on the geographies of energy resources, which will, in turn, determine and influence international relations, with varying repercussions. As a joint consequence of demand expansion in the east and a rapid decline in western dominance of energy trade, the shifts in the existing energy trading patterns are likely to become more profound, resulting in more apparent departures from a familiar set of power dynamics. This was seen in the 1990s, when, after becoming a net importer of crude oil, China resorted to diplomatic means to support its state companies’ efforts to secure energy access, significantly altering the global energy geopolitics and global concerns over energy security, mediated by the rise of emerging Asian consumers against established Western ones (Goldthau, 2012). New alliances that suit regional energy and growth objectives will be forged (Dubash, 2011).

The contemporary global energy systems, encompassing the entire value chain from the extraction of primary energy to its final use, are interspersed with systemic non-linearities, discontinuities and are ridden with widespread uncertainties, marked by rapidly evolving technological, social and economic contexts and frameworks. They are defined by an intricate mesh of exchange networks of suppliers, intermediaries and consumers operating under various market and policy paradigms facing unprecedented challenges while striving to address the challenges of energy security, decarbonisation and the demands for access of modern forms of energy for the ‘bottom billion’ (Goldthau, 2011:213). Energy systems also exhibit wide-ranging externalities of a global scale arising from inherent structural attributes, that simultaneously cut across several policy areas, and the need to deliver on a range of simultaneous goals (Goldthau, 2011). The production of global public goods—such as secure, sustainable and affordable energy access to all—has become a critical challenge that requires arrangements transcending traditional state-specific machinery and national borders (Cherp, et al., 2011). The confluence of all these factors—inherent structural attributes and complexities of energy systems, the challenges it must address, and its transnational characteristics—makes energy systems unique requiring global governance. Global energy governance, or any wide-ranging agreement on a future policy road map between all the relevant stakeholders, will be challenging but critical to achieve (Dubash & Florini, 2011). The desired transition to a net-zero
economy worldwide will be all but impossible without effective processes and functions that are capable and sufficiently empowered to address the challenges facing energy systems transition.

More than ever, processes and functions responsible for governing energy systems need to take strategic, forward-looking decisions based on long-term scenarios that show how various parts of the system interact and consider new trends and uncertainties in technology, markets and policies; and must have the relevant remit, mandate, and flexibility to adapt to these future scenarios, trends and uncertainties and address challenges that emerge. Given the inherent uncertainty and inextricable interlinkages between various parts of the energy system value chain, a fundamentally different approach to previous strategies and arrangements that sought to stabilise emissions will be needed for reaching net-zero emissions by 2050. The need to examine the governance of energy systems adopting a holistic approach, attuned to current realities, in full cognizance of the likely consequences for the future energy pathways and systems has never been more pressing or pertinent than in the current context of energy systems decarbonisation (Florini & Dubash, 2011).

Enabled with appropriate structures, remit and a relevant evidence base, global energy governance presents great potential for facilitating and enabling rapid transition of energy systems. It can prove effective in advancing the Net-Zero goals by facilitating technology transfer and promoting knowledge and learning by creating multilateral interest groups and linkages; establishing guidelines and signals for greater uptake of mature low-\(\text{CO}_2\) technologies; removing high-cost barriers to the uptake, diffusion and use of low-carbon technologies-without handing down significant additional costs to consumers; and setting rules for collective action, for example, on emission reduction target (Oberthür, Khandekar, & Wyns, 2020).

Planning policies and facilitating net-zero transition, however, pose complex challenges; these cannot be addressed through siloed efforts or reductionist approaches. As the interrelationships and interdependencies between various objectives and components of energy systems become complex, both quantitative and qualitative methods employing relevant tools that enable systems thinking framework, allowing for closer examination of relevant feedbacks and uncertainties, and helping capture diverse perspectives to explore the key relationships and feedbacks that will be critical for future energy system transition will be needed. A complex-systems approach can help in examining the impact of feedback and interactions between various relevant sub-system components, and policy choices. It offers greater strategic control on the decision-making process by helping to identify the long-term issues and challenges that impact the development of an area and determine the suitability of policies in meeting the desired outcomes.
Computer models and simulations of physical structures of energy systems incorporating decision and policy rules help to replicate physical systems in virtual form and establishes a closer appreciation of long-term behaviour arising from feedbacks between various parts of the systems. It thus plays an important role in long-term strategic planning (Pfenninger, et al., 2014). Model-based studies of energy systems help in “formalisation of scattered knowledge about complex interactions in the energy sector, and [imparts] a structured way of thinking about implications of changes to parts of the system [...] and allow[s] policymakers [to assess] the directions in which the [systems could be] steered to [achieve the desired] policy goals” (ibid:75). Katine et al. (2020) suggest that modelling and simulation is a faster, cost-effective and efficient way of conducting real-world experiments particularly well suited for understanding the behaviour and performance of 21st century complex systems, such as energy systems, and their problems. Such studies help to capture the complexity and study the effect of interactions between various layers of energy across the decision-making processes. The scenarios about the possible future evolution of the complex energy systems and pathways generated by the models can be invaluable in managing uncertainty and assessing not just the effectiveness of policies pursued in meeting the desired goals, but also in finding reasons behind any shortfalls and frame alternative policies and avoid costly mistakes. Analysing the impact of complex dynamic feedbacks between various interacting energy systems, resources and policy objectives on the long-term energy system trajectory and emerging scenarios is crucial for providing policymakers with an evidence base that they can use for making informed policy choices. This is particularly significant as short-term decisions such as those related to investment in technologies can determine the path of its development, and lead to ‘lock-in’ of incumbent technologies, preventing the uptake of potentially superior technologies in the future (Foxon, 2002).

The future of oil and coal and their place in the energy mix, will, as a natural consequence, determine the success with which decarbonisation objectives can be achieved and impacts the health of the planet. Recognizing the importance of holistic insights for successful and effective governance in the context of net-zero transition and the emerging geopolitics of oil and coal, this thesis adopts a mixed-methods approach to analyse the potential of global energy governance arrangements for leading the net-zero transition and addressing the challenges posed by continued use of oil and coal. It sets out to proceed along these two related domains, exploring the long-term dynamics emerging from the continued use of oil and coal-based generation. Model-based evaluation of scenarios emerging from continued use and expansion of coal in developing countries, championed through the selection of India as a case study, and impacts of fluctuating levels of oil prices on the demand for oil are conducted. These scenarios will yield significant prospects for
assessing the potential of the global governance framework in facilitating energy systems transition. These outcomes present a crucial understanding of the future pathways emerging from specific policy choices with the potential to significantly minimise the risks associated with policy failure.

**Background and Context**

Establishing a coherent policy narrative and stable market conditions is challenging but critical for energy systems transition. The optimum allocation of energy resources has often centred around the principles of the price mechanism and the economics of resource allocation (Allingham & Burstein, 1976:3). These concepts are in themselves complex and much debated. The added dimensions of security of supply and demand, and the immediacy of deep emission reduction targets, makes energy systems governance increasingly more challenging. Against the backdrop of analysing the potential of a global governance framework that can facilitate energy systems transition towards net-zero pathways, while also balancing security and affordability of supplies, the role of oil and coal in the future energy systems is of vital importance. This research is relevant in the present context, as it analyses the possible future trajectories of oil and coal and issues relevant to their governance worldwide.

Coal and oil are the two most important sources of primary energy in the world and have for many decades been vital in shaping the modern-day world. They have steered the course of industrialisation and globalisation and have fuelled the growth of the modern-day world. The level of substitutability between crude oil and coal has reinforced their dominance over a long period. Together, they are also chiefly responsible for degrading the earth’s environment and bringing the world to the brink of an existential crisis. Despite strong and sustained opposition to their continued use to limit the global temperature rise to less than 1.5 °C by 2050, oil and coal are likely to dominate the energy systems in the foreseeable future. In the absence of coordinated global action to stem the rise in carbon emissions oil demand growth will continue to rise in many emerging markets (OxfordEconomics, 2010). Oil demand growth is predicted to be dominated by the petrochemical and growth in demand in India, other Asia (all countries and regions in non-OECD Asia excluding mainland China and India) and Africa, driven by the growing middle class in developing economies, and remains broadly stable at around 100 Mb/d for the next 20 years, before edging lower to around 95 Mb/d by 2050 (BP, 2021). Coal demand, on the other hand, stagnates in the rest of the world but grows within India and other emerging Asian economies to meet the robust growth in power demand from a rapidly expanding population. As international efforts to decarbonise energy systems intensify, the continued consumption of these inherently polluting resources (in the east) is likely to be met with stiff resistance (from the west) (IEA, 2011).
Meanwhile, shifts in global energy power-centres away from Organisation for Economic Co-operation and Development (OECD) countries towards the emerging economies of the east have resulted in significant changes in the order and power bases of the energy world in the recent past (Hirst & Froggatt, 2012). New trade and economic links between the Middle Eastern, African and Latin American producers and East and South Asian consumers have emerged in the recent past (Kalicki & Goldwyn, 2013:4). This shift in the consumer-producer base and trade linkages is likely to alter the current geopolitical landscape even more in the coming years, generating new (geopolitical) dimensions for energy. Further, emerging economies will register unprecedented growth in energy demand to fuel their economic growth.

The role and significance of energy demand growth in developing countries, however, has wider underpinnings beyond the obvious dimension of resource economics into more human-centred issues related to growth and justice (Jenkins, et al., 2016). Besides being a central enabling factor for economic growth, energy also provides access to various fundamental amenities, such as healthcare, education, food storage, water purification etc., rightfully owed to every human being. Developing countries like India, housing a significant proportion (30%) of the global poor, face the daunting challenge of playing a balancing act between developing sustainably but at the lowest cost. With their growing industrialisation and expanding populations, the developing countries are predicted to drive the global energy demand up by 30% between now and 2040 (WEO, 2016). This growth provides greater security of demand for provider nations and creates a more conducive environment for market forces to operate and function than their western counterparts, where demand growth has either plateaued or peaked. The geopolitics of energy, influencing several key aspects associated with the location of energy supplies and demand centres, transit routes and energy prices, becomes a critical consideration in a resource-constrained, but energy-dependent, world. Economics and security of supply of fossil fuels, therefore, create strong incentives for their continued use.

Oil has, over decades, reinforced its role and retained its significance as a global commodity and strategic fuel. The past century has witnessed many changes in the world economy and political order, with ever-increasing concerns over the security and economics of oil-linked primarily to its geopolitics. Oil, upon which, most of the energy industry depends, is sensitive to commodity cycles operated by market forces (Sweeney, 1977; Dale & Fattouh, 2018) and has historically been responsible for triggering widespread shifts in the global geopolitical landscape. The impact of macro-economic fluctuations on energy industries, and consequently, on overall energy geopolitics and social-economic balance is profound and well established (Wang et al. 2017). Energy price shocks seriously impact economic fluctuations and the relationship between the two has been extensively analysed (ibid). With the fundamental role played by oil in nations’ economy, any
fluctuation in its price, or availability, are known to have spill-over effects on the wider macro-economy. Instability in oil prices, uncertainty over its availability and security concerns over its supply (including escalating tensions over transit routes) have together been central to the world’s energy security constructs, and this has, in many ways, propelled industrialised economies to develop non-oil-based energy resources (IAEE, 2014). Oil has even been referred to as a global commodity and strategic resource and has been a subject of widespread investigation and analysis by experts since the oil price shocks of the 1970s (Allsopp & Fattouh, 2016:81; Stevens, 2005).

While oil’s place and role in energy geopolitics has been established for many decades, in more recent times, coal has emerged to be especially significant, given its low price and abundance of supply, which counters the security concerns typically created by oil. It mitigates energy security risks for developing countries like India, which is also the world’s second-largest producer of thermal coal (Garg & Shukla, 2009; EIA, 2019). Significant changes in coal’s otherwise long-term stable trends have taken place in the recent past. China accounted for over 50 per cent of total production up until 2015, and the Asia-Pacific region was expected to represent approximately 80 per cent of the global coal market by 2030 (Accenture, 2013). Despite the recent 1.8% (or 51.2 million tons of coal equivalent (Mtce)) drop in coal demand in China from 2838.7 Mtce to 2 787.5 Mtce, it is predicted to dominate global markets for coal in the future followed by strong growth in demand in India and other Asian economies (World Energy Outlook, 2016:204).

India’s position in the global energy landscape in the foreseeable future will be extremely significant affected by several diverse factors. India is undergoing a phase of unprecedented growth and transformation. Its policies are aimed at building an almost self-sustaining modern economy with a strong manufacturing base, providing an improved standard of living to its rapidly expanding population base which grows from 1.2 billion in 2014 to 1.5 billion in 2030 (with its urban population expanding by over 232 million from 377 million in 2011 to 609 million in 2030), without dramatically increasing its emissions (INDC, 2015). Efforts to provide ‘last mile electricity connection’ to millions of Indians living without access to electricity are already underway. India is predicted to account for a quarter of net global primary energy demand growth between now and 2040 and its power generation is predicted to increase by 207% (BP, 2019). To keep up with the rising demand for electricity, driven by improved prosperity and population growth, “India must add around 15 (gigawatts) GW of capacity each year” for the next three decades (Martin, 2015:2). Coal is predicted to remain the mainstay of electricity generation in India in the foreseeable future. Roughly 42% of India’s demand growth will be met by coal, a majority of which will be domestically supplied (BP, 2019). India has recently revised its renewable-energy target from 175 GW to 227 GW by 2022.
India’s renewable-energy based capacity in 2022, if successfully installed, will be higher than Germany’s net installed generation capacity of 210.78 GW in 2019 (Bundesnetzagentur, 2019).

Despite this striking growth in renewables, coal is predicted to dominate India’s power generation mix in 2040, accounting for 80 per cent of total output. India is already the world’s third-largest CO₂ emitter, despite very low per-capita CO₂ emissions of 1.92 metric tons per year. As India grows, and as its people prosper, India’s total net CO₂ emissions are predicted to roughly double to 5Gt by 2040, increasing its share of global emissions from 7% in 2019 to 14% by 2040 (IEA, 2021). This will be catastrophic not only for India but for the entire world. India’s policy on coal-based generation is, therefore, of great interest and significance globally. While India’s abundant coal reserves ensure long-term energy security for the country at affordable prices, it creates disastrous prospects for the global environment. But there is yet another aspect related to India’s coal use that has a significant global and geopolitical implication. India is also the second-largest importer of thermal coal in the world and India’s energy future significantly determines the global thermal seaborne markets (BrookingsInstitutions, 2019). With ‘falling demand in Europe, North America and Northeast Asia’, India’s policies present substantial implications for global seaborne markets (ibid: iv). As India’s former Environment Minister says, “India’s conundrum is a coal conundrum” and “even with the most aggressive plans to develop nuclear, hydroelectric and renewable power, coal will account for [almost] half the electricity supply by 2030 [and the country needs to intensify its transition towards clean coal and high-efficiency technologies that can in effect reduce the environmental footprint of coal]” (Ramesh, 2015). As international efforts to decarbonise energy systems intensify, the role of technological intervention, which can effectively reduce energy intensity and help countries transit to cleaner energy pathways, will increase in importance. Coal’s future in the 21st century is likely to add significant dimensions into energy geopolitics and governance, and a careful enquiry will be invaluable to decide a future energy roadmap.

The two crucial aspects, therefore, at the unique intersection of decarbonisation and the emerging geopolitics relates to the scenarios emerging from the continued use of coal and oil within the context of wider energy policy objectives and the supply of energy governance capacity in addressing these challenges. These scenarios, inter alia, offer crucial insights into possible trajectories, highlighting the possible gaps, such as the need for global cooperation and lack of regulatory oversight or institutional capacity, that can restrict long-term policy objectives, particularly decarbonisation, and therefore need closer consideration to ensure effective systems and processes that can address the emerging challenges in a timely manner. While continued use of coal and oil benefit the emerging economies to meet their growth objectives, these fail the objectives of decarbonisation. There are unique feedbacks between growth and decarbonisation
objectives that emerge from the continued use of coal and oil, which cannot be captured fully using marginal analysis. There is a dire need to better understand the future scenarios that emerge from the current systems and understand how they behave and respond to stimuli.

In the face of ineffective national energy governance arrangements and policies, it is held, that the global energy governance mechanisms can provide a set of rules and principles that can shape and constrain national policies and avoid situations that can constrain or challenge energy policy objectives. It is, therefore, vital to analyse the framework and architecture of the current global energy governance landscape to assess their potential, or their efficacy, in addressing the challenges facing a net-zero transition in the context of continued oil price volatility and decarbonisation of coal-based generation. The scope and reach of many decision-making bodies and organisations historically central to governance in the energy sector, notably the OECD, the International Energy Agency (IEA), the International Energy Forum (IEF), are believed to be restricted and limited on account of their restricted membership bases (Ramsay, 2013). This highlights the lack of engagement between developed and developing countries and in essence points out the inherent weaknesses in the prevailing structures and mechanisms of global energy governance (Hirst & Froggatt, 2012).

Furthermore, there is little benefit in a retrospective analysis of governance framework, as the biggest challenges to net-zero transition will arise from the future trajectories of oil and coal, or in reforming governance systems to enable energy systems transition without sufficient insight into scenarios about the possible future evolution of the complex energy systems and pathways.

Scenarios generated by models can be invaluable in managing uncertainty and assessing not just the effectiveness of policies pursued in meeting the desired goals, but also in finding reasons behind any shortfalls and frame alternative policies and avoid costly mistakes.

A system-based approach offers greater strategic control on the decision-making process; it helps to identify the long-term issues and challenges that impact the development of an area and determine the suitability of policies in meeting the desired outcomes. Within the said context of net-zero transition, future scenarios and trajectories emerging from continued oil price volatility and expansion of coal-fired generation are extremely significant. Computer models and simulations of physical structures of energy systems incorporating decision and policy rules help to replicate physical systems in virtual form and enable a closer appreciation of long-term behaviour arising from feedbacks between various parts of the systems. The scenarios about the possible future evolution of the complex energy systems and pathways generated by the models are invaluable in managing uncertainty and assessing not just the effectiveness of policies pursued in meeting the desired goals, but also in finding reasons behind any shortfalls and frame alternative policies and avoid costly
mistakes. The long-term dynamics of resources and the prevailing governing context of market and policy dynamics are both vital for energy systems transition.

A careful analysis of policy options, as presented in this thesis, is vital as it saves effort misdirected towards policies that are likely to fail or not achieve the desired outcomes (Fiddaman, 2007:21). Analysing the impact of complex dynamic feedbacks between various interacting energy systems, resources and policy objectives on the long-term energy system trajectory and emerging scenarios will be crucial for generating the evidence base needed for making informed policy choices. This is particularly significant as short-term decisions such as those related to investment in technologies can determine the path of its development, and lead to ‘lock-in’ of incumbent technologies, preventing the uptake of potentially superior technologies in the future (Foxon, 2002). Each of these dimensions needs to be carefully evaluated.

This research bases itself on the new developments that have taken place in the energy systems particularly relevant to two important aspects of the global fossil fuel future: 1) global oil exchanges, and, 2) coal-based power generation in India. Various feedbacks between policy objectives and energy sub-systems are analysed to generate potential scenarios. The dynamics of global resources considering the new socio-economic-political order impacting and arising from changes in global policy directions, such as climate targets, emerging domestic policies on resource use, price volatility, etc. are closely evaluated in this study. The suitability of global energy governance in addressing the challenges highlighted by the scenarios is assessed.

**Research framework and questions**

Transition Studies focusing on addressing the persistent challenges facing contemporary society and leading transformations towards a sustainable society is an emerging field of study gaining popularity over the past few decades (Grin, Rotman, & Schot, 2010). Growing concerns over the societal and environmental risks in recent years have transmitted a widely shared sense of urgency and awareness that our energy systems require fundamental system-wide transformation and are the motivation behind a growing number of studies including this PhD research.

The uptake of renewable-energy based technologies is believed to have ushered in a new era of system-wide transformation in many parts of the world, much like the previous system-wide transitions that occurred in various parts of the energy systems, when coal replaced wood in the 1600s, and when it was, in turn, replaced between the 1940s and 1970s by other hydrocarbons (oil and natural gas) to drive industrialisation. And while the uptake of renewable energy-based technologies may have significantly transformed the energy systems of many countries, other places continue to rely heavily on fossil fuels owing to their inherent social, economic and political
advantages. Addressing these discontinuities is critical for ensuring a just and equitable transition of today’s energy systems to achieve net-zero emissions by 2050.

More than ever, energy policy decisions will need to be more evidence-based and in awareness of the long-term implications of policy choices to facilitate a smooth transition of energy systems. Reactive and short-term decision making will need to be replaced by flexible procedures, which will mandate a more strategic control of the decision-making process. There will need to be, inter alia, more attention on the specification and development of appropriate future scenarios, and their subsequent analyses and inclusion in evidence-base guiding the agenda for any policy reform. This is particularly relevant given the widespread contradictions that exist in different patterns and levels of energy value chain globally, more concerningly related to the future consumption of fossil fuels—notably oil and coal. The conceptual framework of this thesis is presented in Figure 1.1. It consists of theories and concepts of energy systems governance as well as the systems-theory framework which are used together to study the global governance of energy systems in the context of decarbonisation and emerging dynamics of oil and coal.

This thesis is nested within a number of areas and disciplines, drawing on from and building on their inherent strengths and concepts, important to address the complex societal challenge of energy system transition. A Venn-diagram showing the various interdisciplinary linkages between this PhD research and other studies is shown in Figure 1.2. Drawing on from the interdisciplinary studies literature, this PhD research criss-crosses several disciplines—using theories from governance (especially energy governance) studies to set the necessary theoretical foundations, transition...
governance providing insight into the basic tenets of complexity-based governance and using modelling and scenario planning to provide the evidence base to analyse some of the key aspects that this PhD research outlined in the research questions below.

Set against the backdrop of energy systems transitions that are currently underway to achieve various energy policy objectives, notably decarbonisation of energy systems, this PhD research uses a mixed-method approach that facilitates the use and analysis of both quantitative and qualitative data drawing on the strengths of both the methods and diverse perspectives to analyse and uncover the key relationships and feedbacks that will remain critical considerations for future energy system transition. While energy system models provide key insights crucial for addressing the vastly diverse set of challenges, but several other aspects related to energy system transformation are equally key to ensure appropriate design and successful adoption of policies. Qualitative methods help to test and refine the insights generated by energy system models. Attempts to use social science methods to capture the human dimension in energy system models exist but are grossly under-represented in contemporary energy research (Sovacool, 2014). While model-based analyses into evolving dynamics of oil and coal remain the main method of enquiry, a purposeful mixing of methods is carried out at relevant stages of this research to aid data collection, data analysis and interpretation of evidence allowing for a more panoramic view of the research landscape and suitable adoption of appropriate viewpoints. A high-level schematic outlining the approach undertaken for this PhD research is shown in Figure 1.3.
Qualitative aspect of this PhD research includes document analysis, which both precede as well as follow quantitative model-based analyses and is described in chapter 2. Relevant theories and concepts of systems-thinking and governance are analysed in chapters 2 and 3 respectively, which, in turn, are used to inform the quantitative enquiries, allowing not just a deeper understanding of specific context but also to test and extend the concepts and theories through the quantitative approach. Document analyses of theories and construct of governance studies and systems thinking framework coupled with policy documents provide the context and supplement the model-based enquiries through system-dynamics models and the insights provided by them into various future scenarios. The debate on epistemological incompatibilities is deliberately avoided in favour of focussing on the potential benefits that come from combining qualitative and quantitative approaches in this study (Walker and Baxter, 2019). As emphasised by Patton (1990) in ‘paradigm of choices’ who rejects the orthodoxy of methodology in favour of appropriateness of method to the specific context of the research, the primary criterion guiding the research design for this PhD research has been dictated by the nature of enquiry underpinned by the research questions and the underlying context of this research—which is restricted to examining the two most prominent barriers to decarbonisation—continued use of oil and coal as they are likely to be the biggest barriers posing systemic challenges to energy system transition in the 21st century.

It cannot be denied that effective transition of future energy systems towards decarbonised pathways will only be complete in so far as they are also just, equitable, affordable and secure.
Widespread disparities prevail between the sought goals and current realities across most, if not all, energy policy objectives. For example, carbon emissions continue to increase despite climate reduction targets and ambition; or, approximately one billion people around the world lack electricity access notwithstanding the promise of free and clean energy for all (IEA, 2020). Issues of equitable access and just transition will predicate the degree of successful energy system transition, these are simply considered as more embedded into current policy considerations and excluded for posterity. And therefore, considerations around energy justice, energy security, etc. that are all extremely significant in their own right and deserve separate enquiries, are simplistically introduced and alluded to at various relevant places in this study.

While aspects related to global energy governance are subjects of considerable literature, but for the most part, these analyses do not consider structural changes backed by evidence provided by scenarios developed by adopting a complex-systems approach. It is a major gap in global energy governance studies that this PhD thesis seeks to address.

Model-based enquiries are undertaken using system dynamics methodology, which has proven effectiveness in analysing the impact of feedbacks and non-linearities. System dynamics models show how structure and amplification in policies and time delays in action and decisions can interact and generate feedbacks that can explain the behaviour of a complex system over time and therefore lends well to the design and execution of complex system governance (Katina, Tolk, Keating, & Joiner, 2020). Scenario planning is an established method and has been used in the energy sector for over forty years with great success (Benedict, 2017), however, its application in global governance studies was not found. The scenarios in this thesis are developed using a system-dynamics methodology and used to assess the impact of current policies on long-term energy policy objectives. These help to analyse the outcome of policy choices and provide a coherent insight into the likely future of energy system decarbonisation.

The range of uncertainty in future projections made in various studies cited above is understandably significant as these are based on future policy assumptions and claims. Uncertainty and feedbacks are the two most significant aspects that determine the future energy system pathways and cannot be ignored. This is one of the motivating reasons for using system dynamics-based enquiries in this research, as it takes into account the important feedbacks and nonlinearities within a system and helps to analyse how changes within any element of the system affect the system as a whole. Additionally, a Monte-Carlo simulation using the @Risk platform is also carried out to explicitly study

---

2 "Scenario planning was first used effectively by Royal Dutch Shell approximately 40 years ago. The premise of scenario planning is that possible future trends are analysed and the capability of policy processes in dealing with these scenarios is assessed." (Benedict, 2017)
the likelihood of some of the future solutions emerging from the coal model. A risk-based analysis is deemed relevant to the India study given the decision making occurs through non-market mediated principles.

The aim of this study is to undertake a systematic study of the system led behaviour and to broaden our understanding and views about the various states or scenarios a future system could potentially generate and in doing so enable decision-makers to make informed policy choices. Consideration of these issues is also important to understand and bridge the debilitating gap that currently exists in the energy governance framework that creates a further barrier to effective energy system transition. Global governance processes and frameworks play an important part by fostering international cooperation and strengthening the policy framework to advance the decarbonisation objectives by addressing the barriers to it and by offering suitable means of implementation (technology transfer, capacity building). However, a careful restructuring may be needed as the institutions, arrangements, linkages that currently exist are not fit for purpose. The scenarios developed by the model highlight the gaps that provide significant direction for global energy governance reform to suitably address the barriers.

The thesis is structured to proceed along the premise outlined by the following research questions while simultaneously attempting to find answers to each of them. In answering these questions, this PhD research establishes its specific relevance and contribution—both through the outcomes, but also crucially through the process of enquiry to the field.

**Overarching Research Question for the PhD**

*How will the emerging dynamics of resources impact the future transition of energy systems towards decarbonised pathways, and the global governance of energy?*

The hypothesis this question carries is that an efficient governance framework and arrangement for the energy sector is required to address the challenges of the 21st century. Energy policies intersect a wide range of policy areas including geopolitical, socio-economic, developmental, political and environmental dimensions, and a cohesive framework that governs energy across various barriers must, therefore, contain mechanisms and legitimacy to deal with a number of cross-cutting issues in order to address various emerging challenges and barriers to implementation. Given the cross-cutting nature of the energy landscape and a fairly large number of issues that energy governance should effectively focus on, is the current energy governance framework empowered and effective in addressing the various challenges acting as barriers to energy systems transition?
The enquiry into this question is aided through the review of existing theories of governance, global energy governance paradigms and a careful assessment of the current global energy governance architecture. These theories provide the philosophical underpinnings that guide this research. The prevalent landscape of energy governance is outlined through a review of literature that seeks to unravel the basic tenets of the energy governance framework associated with: What are the objectives and scope of Global Energy Governance (what in energy needs to be governed)? Who governs energy? How is energy governed?

The results from global oil and Indian coal system dynamics models help to assess the efficacy of the current global governance arrangements in overcoming the barriers to effective transition to decarbonised energy systems that arise from continued consumption of oil and coal. The work presented in this thesis distinguishes itself from the current literature on energy governance in that it does not take a prescriptive approach to define an effective governance framework simply normatively or, retrospectively. This thesis is less concerned with finding generalisable theories but instead with providing the evidence base and an analytical foundation that can aid policy scholars and governance theorists and practitioners in analysing the efficacy of current governance arrangements and to engineer holistic, long-term energy governance arrangements that are effective in addressing the challenges facing energy systems transition—a key objective of energy policies globally. This thesis does not, as such, apply theory in order to “…aspire to predict or to prescribe...” and is a non-normative, reflective approach to the subject area (Strange 1988: 11 and 19). The thesis is more focused on assessing the impact of the current state of the system on the possible future trajectories it may generate; and eventually on identifying a rational way to reform the existing systems to achieve system-wide changes.

This thesis approaches energy governance as a set of underlying principles, processes and arrangements through which policies are negotiated, framed and implemented. The use of concrete evidence-base from model-based analyses is used as an aid to help in overcoming marginalisation and cognitive boundaries that can limit any alternative ideas about how to approach global energy governance and can be effective in initiating the process of ‘re-think’ about how the existing framework can be modified towards goal-achieving structures.

While the evidence base in this thesis is empirical in nature, preliminary boundaries for the research are structured using a mixed-methods conceptual framework, using archival research of policy documents, review of existing theories and even in some cases conversations with policy professionals and officials from various government departments, in order to provide a more realistic grounding to this work. The insights from this study can also help in consolidating the
existing frameworks or institutions of energy governance and can help them evolve and adapt to future requirements. The following sub-questions are developed to help delve deeper into specific issues that will help to answer the overarching research question.

**Research Sub-Questions and Objectives**

**Question 1:** How will the long-term dynamics of fossil fuel resources, notably oil and coal, impact the future of energy systems decarbonisation?

**Objective:** This question sets the broad framework of enquiry that is presented in this thesis. The objective is to analyse the scenarios that are likely to emerge from interactions and key feedback between relevant policies and system structure. The enquiry into this question is carried out through the following sub-questions. The oil model provides insight into the future trajectory of oil demand resulting from unsettled oil price points and the coal model explores the impact of continued use of coal for power generation in India resulting from its overlapping policy objectives.

**Sub-question 1:** What will the future effect of oil price points be on the demand for oil?

This sub-question is vital to this research as it helps to understand the likely paths that may arise in the future depending on the policy choices of key stakeholders. The enquiry is based around the consequences of price shocks on the global economy. The political economy of oil together with the mechanisms of oil price formation serve as the starting point of investigation and guide the development of an integrated model of global oil exchanges using system dynamics through which the likely future scenarios are constructed, and their implications, that may arise as a result of varying price signals, are analysed.

A system-dynamics model of global oil exchanges is developed, which seeks to provide insight into the future trajectory of oil demand resulting from unsettled oil price points. This model is anchored around oil price and facilitates a rational representation of physical stocks, flows and non-linear causal exchanges that drive decision-making in the system. The dynamic hypothesis of the model is based on feedbacks between demand, supply and price determinants of oil.

The scenarios resulting from supply-side shocks are linked to energy security. A further scenario that is based on the impact of a future climate response is also tested to examine the likely changes in oil demand as a possible consequence of growing pressures of decarbonisation. These scenarios help to analyse the different future feedbacks between oil price and demand dynamics.

**Sub-question 2:** What will be the impact of India’s overlapping energy policy objectives on coal use for power generation and India’s carbon emissions pathways?
Objective: The enquiry into this question begins with an enquiry into the key factors globally that are likely to be significant for coal’s overall future in the 21st century. The objective is to understand and outline the basic facts about coal that reinforces, or will be significant in deciding, its use and future. Understanding the market and policy considerations specific to coal is key to understanding the role it may play in the future, and how it may evolve—which are both often misunderstood or not understood well. The challenges posed by coal’s continued use are somewhat naively side-lined and often even ignored. Initial consideration of the issues would suggest that the expansion of coal use is inevitably an environmentally damaging path, which policymakers should seek to avoid, as have some countries, which have systemically moved away from apportioning any significant role for coal in their energy mix in favour of cleaner sources of energy. This, however, is not the case in all parts of the world. Coal, today, does much to supply affordable energy to the world’s poorest.

To what extent, then, might it be possible to meet their needs in a more environmentally responsible way? These key facts will be crucial for future framing of policies and remain central to the enquiries undertaken in this thesis. The socio-economic and political realities lock some countries into continued consumption of coal and need to be acknowledged so that necessary support and timely intervention can be made available. All these set the foundation and outline the context for a closer evaluation of the impact of overlapping energy policy objectives on coal consumption for power generation in India.

The India coal SD model examines the possibility of deep decarbonisation of India’s power generation systems under its current policy landscape. The CO₂ emissions from India’s power generation continue along an S-shaped curve, emerging from interactions between policies that seek to both boosts as well as balance coal-fired power generation. A set of policy scenarios, that represent the business-as-usual, a scenario of deep climate action through a greater share of more efficient coal-based technologies and, finally a scenario using advanced coal technologies enabled with CCS are tested.

The scenarios developed from the model form the basis for the techno-economic assessment into a range of clean-coal technologies that are widely believed to effectively reduce energy intensity and help India meet its carbon emission reduction targets. But uncertainties abound. The costs and benefits associated with the transition from the current fleet of coal power plants to low and zero emission options in India’s (unique socio-economic) context are examined using a Monte-Carlo simulation perform using @Risk software, which considers a range of uncertainties into relevant parameters.
A review of market data on current or projected trends is undertaken. Several global institutions, such as the British Petroleum (BP) and IEA, routinely publish energy statistics and market outlooks based on the current trends. Understanding these trends and projections provide the essential data and set the foundation upon which this study builds itself. A closer study and analysis of the trends and projections help to evaluate the policy priorities of emerging economies like India vis-à-vis reduced import dependencies, emission reduction targets etc. and its impacts on the existing policy trajectory.

**Thesis Organisation**

The conceptual framework and the research questions that constitute the principal structuring element to this thesis have been suggested in the preceding sections. Chapter 2 provides the methodological grounding for this research and outlines the rationale behind the selection of complex-systems studies. The chapter reviews a range of methods and assesses their suitability for this study and establishes that complex systems dynamics is best suited to this PhD research. Additionally, the step-by-step methodology employed in this research is also outlined.

Chapter 3 presents a review of the literature on governance and global energy governance, highlighting various aspects of global energy governance paradigms, frameworks and processes relevant to this PhD research. The review criss-crosses various scholarly lenses and aspects, each lending a specific context to this research. These existing ideas and philosophies guide the enquiry by offering theoretical boundaries and an ideological framework for this research. The review of literature serves to identify the relevant gaps in the functions and processes of global energy governance and lends relevance to the work carried out in assessing the potential of global energy governance to lead the transition towards decarbonisation.

In Chapter 4 an overview of global oil dynamics is presented, together with a detailed system-dynamics based analysis of various scenarios that the oil price signals can generate. This chapter establishes that oil price levels will be critical determinants of a future world order of dominant suppliers and consumers of oil.

Chapter 5 explores the future of coal in the twenty-first century at a time of widespread uncertainties and incongruence in policy narrative, and a relatively increasing dominance of emerging countries as they emerge as the biggest consumers of energy and in the context of upcoming technological innovations. The chapter establishes that economics and security of supply emerge as strong incentives for the continuing use of coal in many emerging countries but given the scale of anticipated expansion of coal-based generation in India, it is likely to emerge as one of the biggest emitters of carbon dioxide in the world.
Chapter 6 presents the implications of an expanding coal-based power generation in India as a result of policy priorities of sustained growth at the lowest cost based on an SD model that analyses the crucial feedbacks between various policy objectives in the country. The chapter concludes that under the current policy landscape, while India may succeed to achieve its Paris commitments to reduce the emission intensity of its GDP with the planned move to supercritical coal technologies, it may not be possible to stabilise CO₂ emissions growth without a wide-scale shift to advance coal technologies enabled with growing economic growth in India.

The role of clean coal technology and its implications for India are presented in Chapter 7. This chapter presents an in-depth techno-economic feasibility assessment of a range of clean coal technologies relevant in India’s context. The risk and uncertainty which surrounds the transition from the current fleet of sub-critical and supercritical power plants to zero-emission technologies are assessed. A theoretical review of the geological CO₂ storage potential in India’s deep saline aquifers, depleted oil and gas fields, un-mineable coal seams and volcanic rocks is also presented in this chapter. Chapter 8 summarises and brings together the findings from various parts of this thesis and assesses the potential of global energy governance for facilitating decarbonisation of energy systems and presents recommendations for future work.
Chapter 2: A mixed-methods approach to the Governance of Energy Systems

Overview
Attempts to explain global governance in the context of energy systems decarbonisation are often fragmented, focusing on specific rationale or perspective of specific stakeholders. Recognizing the importance for holistic insights for successful and effective governance in the context of net-zero transition and the emerging geopolitics of oil and coal, this thesis adopts a mixed-methods approach to analyse the potential of global energy governance arrangements for leading the net-zero transition. The use of both quantitative and qualitative methods enables to capture diverse perspectives to explore the key relationships and feedbacks that will be critical for future energy system transition.

Mixed-methods approach
Mixed methods research, which is the combination of qualitative and quantitative techniques, methods, approaches, concepts or language in the same study, originated in social science but has recently been expanded into health and medical as well as environmental studies (Wisdom & Creswell, 2013). The method has developed rapidly over the last two decades emerging as a distinct method with an established identity. A methodological review of mixing research methods and its application in the field of environmental management and sustainable development is available in the study by Molina-Azorín & López-Gamero (2016), who posit that combining results between different methods or combining different research methods to specific aspects of a given research can effectively enhance the validity of inferences.

The mixed-methods approach used in this thesis allows the concurrent or selective use of procedures based on the objective and scope of enquiry, whereby the qualitative or the quantitative method selectively dominates the research findings across relevant aspects and enable closer examination of results. The benefits of this approach are well established. Authors like Shorten and Smith (2017) suggest that mixed methods research have a distinct advantage as they draw on potential strengths of both qualitative and quantitative methods and allow researchers to closely examine the complex phenomenon evaluated by the research and between various intricate layers of multifaceted research questions, using different viewpoints and using diverse theoretical lenses and even by triangulating one set of results with another, which enhances the validity of inference. Cresswell and Plano Clark (2007) stated that by combining qualitative and quantitative methods, a better understanding into research problems and complex interlinkages can be gained than with a
monomethod approach. Mixed-method (formerly called multi-method) approaches are now commonly used both as an approach to design research as well as a distinct research method (Timans, Wouters, & Heilbron, 2019). A significant factor in framing mixed methods design is determining the priority of approach relevant to the research. Molina-Azorin (2016) states that mixed methods offer flexibility to the researcher in apportioning priority to the method determined based on scope of research, construct of questions or other practical constraints such as the availability of data. Following this approach, a nested design of qualitative and quantitative methods is used in this PhD research (Shorten and Smith, 2017). Molina-Azorin and Lopez-Gamero (2016) explain that a research can be designed in a variety of ways, based on the selected combination of methods (or dimensions) - qual and quan; resulting in four groups and nine different types of mixed-method design, which are often denoted using the notation proposed by Morse (2003). Capital letters are used to indicate the dominant method (QUAL, QUAN) and small letters for the supporting method (qual, quan) while symbols are used to denote the relationship between the two dimensions; ‘+’ indicates simultaneous and ‘→’ indicates sequential design ( ‘||’ is used to indicate parallel combinations) (2016:136). Based on this notation, the framework of research design in this PhD can be denoted as qual || QUAN ↔ qual.

Other purposes of mixed methods approach, notably: complementarity- where findings from one method help to elaborate, illustrate, enhance, and clarify finding from the other methods; development- where concepts and observations from one method can elaborate and illustrate insights gathered from the other method; and expansion-where the two methods help to mutually extend and enhance the enquiry into various component of study, are relevant to this PhD research.

Document Analysis

Document analysis is a form of qualitative research which employs the use of documents to interpret and extend the findings around an area of interest. Document analysis is a systematic process that allows the review and analysis of ‘both printed and electronic material’ (Bowen, 2009, p. 1). Also sometimes referred to as content analysis or extant data analysis, it is a process of analysing facts or trends in existing documents.

The documents used in document analysis can, according to Bowen (2009), take a variety of forms and include, ‘advertisements; agendas, attendance registers, and minutes of meetings; manuals; background papers; books and brochures; diaries and journals; event programs (i.e., printed outlines); letters and memoranda; maps and charts; newspapers (clippings/articles); press releases; program proposals, application forms, and summaries; radio and television program scripts; organisational or institutional reports; survey data; and various public records’ (ibid). Document
analysis is an established method that can be applied to the review of documents of all types, including non-technical literature, such as reports and policy-focussed interviews, which can be potentially significant in helping understand the context and discover insights relevant to the research problem (Mills, Bonner, & Francis, 2006).

While document analysis is a research method in its own right, it is widely used as a part of mixed-methods approach in order to seek convergence and corroboration between results from quantitative methods and concepts from qualitative methods. A number of studies have previously used document analysis as the qualitative research method in mixed-method studies given its role and value in methodological and data triangulation (details and examples in Bowen, 2009; Caracelli & Greene, 1993).

Documents are of key significance in this PhD research as they provide data on the context within which the research is set; documents also support and validate the enquiry carried out and insights generated by the quantitative aspects of this research; they provide supplementary data and provide a means for tracking change and development; and finally they help to corroborate evidence between various sources (Bowen, 2009). Document analysis provides for an efficient, easily available, cost-effective, stable, exact, unobtrusive and non-reactive research method, however, can suffer from biased-sensitivity if the source and collection of documents is not suitably expanded (ibid). Various published documents, from a wide variety of sources, including, literature, industry reports and relevant policy white paper are analysed to both set the theoretical foundations upon which the research builds itself as well as to assess wider implication of insights generated by the model-based studies.

Document analysis is an extremely relevant and effective method for setting the conceptual framework and foundation for this thesis. The framework and architecture of the current global energy governance landscape is analysed to assess their potential in addressing the challenges facing net-zero transition in the context of continued oil price volatility and decarbonisation of coal-based generation. A majority of energy governance scholars including, among many others, Van de Graaf (2016), Dubaash & Florini (2011); Florini & Sovakool (2009); Goldthau & Witte (2010); Lesage & Van de Graaf (2016) have extensively used document analysis to systematically analyse in some notable contributions in the field of energy governance scholarship. This thesis has relied extensively on document and content analysis, as presented in Figure 2.1, including data analysis for system dynamics models as well as for assessing the potential of global energy systems framework for facilitating energy systems decarbonisation. Document analysis has also helped to assess and
establish the suitability of systems thinking tools for energy systems governance scholarship, as employed in this PhD research.

**Figure 2.1: Use of document analysis for setting the background, context and for carrying out analysis**

**A Systems Approach to Complex Energy Systems**

The issues associated with the effective governance of complex systems have been discussed for quite some time with little consensus on the way forward. The challenges facing global energy systems, in the meantime, have grown manifolds, and need to be addressed urgently and simultaneously. These arise given the role of energy as an essential resource for achieving economic and development goals and affecting environmental sustainability. The challenges associated with transition to low-carbon (now net-zero) energy pathways, exacerbate in the face of rapidly rising energy demand, continued reliance on fossil fuels, and the lack of access to clean and reliable forms of energy for billions of people. The problems of investment and funding, already of a daunting magnitude, are magnified by the increasing interdependence of energy systems and the transnational nature of its externalities. Fewer states can rely solely on their own resources to meet all their energy demands and needs and address all the challenges these pose. This becomes more apparent with developing countries emerging as the biggest consumers of energy and lacking, in most cases, the wherewithal to mobilise technological solutions such as carbon capture and storage, advance storage solutions, smart grids etc. that have the proven capability elsewhere to implement successful energy transition.
Evolution of Energy Systems as Complex Systems and Use of Systems Thinking Paradigm

Energy systems, ‘defined as the process chain (or a subset of it) from the extraction of primary energy to the use of final energy to supply services and goods’, have, with increasing systemic interdependencies and transnational externalities, acquired the core characteristics of complex dynamic systems (GEA, 2012). According to Cherp, Jewell and Goldthau (2011), a system can be said to have acquired the characteristics of complexity if it cannot be predicted, comprehended or, transformed easily. The shared attributes between energy systems and the core characteristics of complex systems as conceptualised by social and natural sciences, also summarised in Table 2.1, clearly show that energy system behaviour is influenced by dynamic uncertainties, nonlinear relationships between system variables, time lags, and interactive feedback loops that are intrinsic to complex systems.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Complex Systems</th>
<th>Energy Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnectedness</td>
<td>Large number of interacting elements with feedback loops and intricate relations between constituent parts.</td>
<td>Energy systems comprise a multitude of interconnected elements throughout their production, distribution and consumption supply chain network.</td>
</tr>
<tr>
<td>Unpredictability</td>
<td>Past trends in behaviour do not generate reliable foresights into future behaviour.</td>
<td>Energy systems are strongly path-dependent and are also capable of undergoing rapid, unpredictable changes.</td>
</tr>
<tr>
<td>Path dependence</td>
<td>The evolution of a system is often irreversible, and the system behaviour can follow along the set path.</td>
<td>Due to technological, institutional, and behavioural lock-ins, energy systems are subject to strong and long-lived path dependence.</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>Minor changes can result in disproportionately major consequences.</td>
<td>Minor deflections in input such as policy signals or investment decisions can result in major deflection in system behaviour.</td>
</tr>
<tr>
<td>Openness</td>
<td>The boundaries of complex systems are seldom clearly defined; they exist in a flux interacting freely with the surrounding environment.</td>
<td>Energy systems openly interact with natural, social, and technological systems.</td>
</tr>
<tr>
<td>Adaptability and resilience</td>
<td>Complex systems can adapt to external circumstances and preserve their patterns even under external pressures and shocks.</td>
<td>Energy systems can preserve their function under changing external circumstances. For instance, energy security strategies of both importing and exporting countries can respectively resort to keeping spare capacities in the systems or using diverse supplies, and by using market power to stabilise price signals to maintain resilience.</td>
</tr>
</tbody>
</table>

Source: Adapted for this thesis from (Cherp, Jewell & Goldthau, 2011)

With advancements in energy technologies; evolved energy geopolitical landscape with the emergence of new aggregate consumers, producers and traders of energy resources; prominence of new global concerns (such as climate change and energy equity) altering the overarching policy narrative and goals; and with the indomitable shift of energy systems towards extremely complex systems, the need for strategic tools that can enable a successful transition of twenty-first century energy systems towards the sought objectives can hardly be overstated. The problems stemming
from dynamic complexity of energy systems, arising from its underlying interdependencies and exchanges, pose a serious dilemma for traditional forms and modes of governance.

In the face of these compounding complexities inherent in contemporary energy systems, nation states and traditional governance mechanisms are believed to be ineffective in regulating and governing energy related issues on their own (Cherp, Jewell, & Goldthau., 2011). While these traditional centralised arrangements ensure coordination through vertical top-down linkages and efficient division of function and transmission of information, relying too heavily on these hierarchical arrangements may (and often do) exclude connections and linkages that lie outside their structure, thus, failing to take some of the crucial feedbacks into account.

The traditional static arrangements also debilitate flexibility, diversity, experimentation and innovation which are all proven invaluable in dealing with uncertainty and nonlinearity (Cherp, Jewell, & Goldthau., 2011). With intensifying complexity, nonlinearity and changes in energy systems, traditional tools may not just fail to solve or fully evaluate the problems, they may in fact even exacerbate the problem by creating unanticipated side effects (Sterman, 2000). This may, as Sterman argues, in fact end up creating policy resistance- ‘the tendency for interventions to be defeated by the response of the system to the intervention itself’ (ibid). John Sterman elaborates this by quoting the late biologist Lewis Thomas (1974, 90):

“…when you are confronted by any complex social system, (...) with things about it that you’re dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping. This realization is one of the sore discouragements of our century...You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn’t counted on in other, remote parts. If you want to fix something, you are first obliged to understand...the whole system. Intervening [in siloed parts] is a [guaranteed] way of causing trouble.”

The solution to the conundrum, posed in the quote above and encountered across a number of failed policies (examples in Sterman, 2002), is offered by the systems thinking paradigm, which offers the ability to adopt a holistic worldview to understand how things are connected and in turn helps in identifying sensitive parameters and leverage points that can be effective in avoiding policy resistance.

**A systems-thinking approach for complex systems in transition**

Use of systems thinking paradigm for studying complex systems has gained traction across various prominent spheres of research and decision-making bodies. A recent study jointly undertaken by the
Organisation for Economic Co-operation and Development (OECD) and International Institute for Applied Systems Analysis (IIASA) identifies the potential of systems thinking and framework in addressing critical global issues and guiding policy options (Ramos & Hynes, 2019). It maintains that as most twenty-first century challenges are ‘fundamentally systemic’ and interconnected, and create complex, connected systemic issues, these ‘cannot be managed by ad hoc, short term, sectoral interventions’ (ibid: 3). A reductionist approach and paradigm- where complex realities are separated into specialised disciplines, fields of research, agencies, and ministries, the authors from the OECD-IIASA study suggest, only focus on one part of the overall problem, often resulting in disparate views that fail to materialise into effective policy responses (ibid). In reference to global energy system governance (or, global energy governance), Cherp, Jewell and Goldthau in their scholarly work on Governing Global Energy: Systems, Transitions, Complexity argue that an effective framework for global energy governance cannot be achieved within a single agency or framework, but through a polycentric approach requiring a ‘tenuous balance between the determination and efficiency needed to drive [the required] energy [systems] transition with the flexibility and innovation needed to deal with complexity and uncertainty’ (2011, p. 75).

A number of studies highlight the importance of holistic framework for designing a successful transition governance for sustainable development. While these theories can be seen nested separately within the literature on transition governance, they are extremely relevant in the context of governance of, or for, energy systems transitions (Halbe & Pahl-Wostl, 2019; Könnölä et al. 2009); (Loorbach, 2010)). The unifying strand through this growing body of scholarly work is that effective transition towards energy decarbonisation policies should be based on insights generated from both governance and complex systems theories (Loorbach, 2010). With intensifying energy system complexity, and with the emergence of long-term persistent societal problems holistic approaches that consider system-wide interactions will be needed, especially as short-term solutions create policy resistance and often lead to sub-optimal changes in the structure of the system, in turn transforming the problem itself, climate change being an example (ibid).

Systems thinking is widely held as a practice that results in successful policies for complex systems as it offers a ‘more-integrated perspective through a number of proven concepts, tools and methods that improve our understanding of the complex systemic issues which threaten the future’ (Sterman, 2000). Systems thinking together with its concepts and tools helps to uncover how changes in specific parts of the system elements impact the overall system behaviour and thus have much to contribute in responding to the twenty-first century challenges of deepening energy system complexity and for development and evaluation of energy system governance, both at tactical and strategic levels (ibid). In his seminal work on systems thinking, The Fifth Disciple, Peter Senge
classified systems thinking as one of the five core learning disciplines and described it as a way of thinking about the forces and interrelationships that form the behaviour of the system. Senge describes in this work that the ‘structure’ of a system ‘influences its behaviour’ and ‘more often than we realise’ the systemic behaviours are influenced by the basic interrelationships within a system.

Senge further explains that approaching problems from a system perspective can help to unravel the underlying structures responsible for the problem behaviour. Additionally, the systems perspective also offers an important means to analyse the explanations to a given complex situation. An event-level explanation—who did what to whom, explains Senge, ‘doom their holders to a reactive stance’ and is also the most commonly held perspective; a pattern-level explanation, on the other hand, focuses on assessing long-term trends and their implications (Senge, 2004:40). The latter has broader boundaries than event-level explanation. And finally, the structural explanation, the last common and also the most powerful level of explanation, explains Senge, focuses on the causes of a given behaviour at a level that the said pattern of behaviour can be modified by modifying the structure, and is, therefore, generative in nature. Senge explains that ‘structure of a system produces its behaviour’, and ‘changing the underlying structure [of the system] can modify its behaviour patterns’ (ibid).

Other definitions of systems thinking can also be found; each offering unique insight into specific aspects of systems thinking paradigm. Arnold and Wade (2015) review the definitions by some of the most famous systems thinkers examining their definition against a system test framework in an effort to systematically determine how closely they meet the essential requirements for an overarching system thinking definition: purpose-describing the purpose of systems thinking clearly; element-description of the characteristics of systems thinking; and interconnections-description of how systems thinking elements relate to each other (ibid). A systematic comparison of various definitions analysed by Arnold and Wade is presented in Table 2.2.

The definitions listed in Table 2.2 provide an extensive insight into various key attributes offered by systems thinking paradigm. Put simply, systems thinking provides a framework for seeing overarching interrelationships between various constituent parts of a system and provides vital insights into emerging systems behaviour over time driven by intrinsic properties and feedback. It, therefore, applies well to mapping a successful roadmap for energy system transition which mandates coordination and coherence across timescales transcending narrow systemic boundaries.
### Table 2.2 System Thinking Definition by famous systems thinkers

<table>
<thead>
<tr>
<th>Authors</th>
<th>Systems Thinking Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richmond (1994, pp. 5-7)</td>
<td>Systems Thinking is the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure. [...] Systems thinking is a paradigm and a learning method, which consists of vantage point and thinking skills, which in turn determine the position within the fray as well as the meaning of this perception.</td>
</tr>
<tr>
<td>Senge (1997, p. 53)</td>
<td>Systems Thinking is a discipline for seeing wholes and a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots. It is a set of general principles—distilled over the course of the twentieth century, spanning fields as diverse as the physical and social sciences, engineering, and management. It is also a set of specific tools and techniques, originating in two threads: in “feedback” concepts of cybernetics and in “servomechanism” engineering theory dating back to the nineteenth century.</td>
</tr>
<tr>
<td>Sweeney &amp; Sterman (2000, p. 250)</td>
<td>[...] the art of systems thinking involves the ability to represent and assess dynamic complexity (e.g., behaviour that arises from the interaction of a system’s agents over time), both textually and graphically. Specific systems thinking skills include the ability to: understand how the behaviour of a system arises from the interaction of its agents over time (i.e., dynamic complexity); discover and represent feedback processes (both positive and negative) hypothesized to underlie observed patterns of system behaviour; identify stock and flow relationships; recognize delays and understand their impact; identify nonlinearities; [and] recognize and challenge the boundaries of mental (and formal) models.</td>
</tr>
</tbody>
</table>
| Stave & Hopper (2007, pp. 11-13) | Providing a review of existing literature on systems thinking, the authors maintain that a systems thinker:  
1. Thinks in terms of “wholes” rather than “parts” (c.f. Richmond, 1997)  
2. Recognizes/seeks to understand interconnections and feedback (Ossimitz, 2000; Potash and Heinbokel, 1997; Richmond, 1997; Sweeney and Sterman, 2000)  
3. Understands the concept of dynamic behaviour (Ossimitz, 2000; Potash and Heinbokel, 1997; Richmond, 1997; Sweeney and Sterman, 2000)  
4. Thinks in terms of the system as the cause of its behaviour (Ossimitz, 2000; Richmond, 1997; Sweeney and Sterman, 2000)  
5. Understands the way system structure generates system behaviour (Ossimitz, 2000; Richmond, 1997)  

The authors compared several key components and the continuum derived from the literature and proposed that a taxonomy of systems thinking characteristics should: recognize interconnections; identify feedback; understand dynamic behaviour; differentiating types of variables and flows; use conceptual models; create simulation models; [and] test policies. |
| Squires, Wade, Dominick and Gelosh (2011, p. 4) | Systems thinking is the ability to think abstractly in order to: incorporate multiple perspectives; work within a space where the boundary or scope of problem or system may be “fuzzy”; understand diverse operational contexts of the system; identify inter- and intrarelationships and dependencies; understand complex system behaviour; and, reliably predict the impact of change to the system. |
| Forrester (1994, pp. 11-13) | Forrester considers systems thinking as a subset of system dynamics and states that system thinking implies ‘thinking about systems, talking about systems and acknowledging that systems are important, […], and usefuly provide a general public introduction to the existence and the importance of systems’. |
| Arnold and Wade (2015, pp.675) | Systems thinking is a discipline that helps in seeing the whole rather than just its constituent parts and is a framework for seeing overarching interrelationships rather than static one-way flow of events. It contains elements that: recognise interconnections; identify and understand feedback; understand system structure; differentiate types of stocks, flow and variables; identify and understand non-linear relationship; understand dynamic behaviour; reduce complexity by modelling systems conceptually; reduce systems at different scales. |


### Systems thinking tools and methods

A systems-based approach to policy making refers to the application of concepts and constructs of systems theories, philosophies and models to the theories and principles that lead to a governing course of action (De Greene, 1993). Systems thinking methods have been used since the 1970s to
evaluate complex policy systems. Many scholarly works provide a detailed review of systems thinking tools and methods. According to Gates (2016) while causal loop diagrams and system dynamics, agent-based modelling, soft systems methodology, social network analysis, critical system heuristics are some of the commonly used methods that have been in use for many decades, new methods such as developmental evaluation, systemic evaluation, systematisation, modified versions of responsive evaluation and theory-based evaluation have recently been used to study and evaluate complex systems (Gates, 2016).

Another extensive account of system-thinking tools is presented by Kim (1990), who lists ten different types of systems thinking tools categorised under four broad category: brainstorming tools (includes double-Q diagramming, or, qualitative-quantitative diagramming); dynamic thinking tools (includes behaviour-over-time, causal loop diagram, system archetypes); structural thinking tools (includes graphical function diagrams, structure-behaviour pairs and policy structure diagram); and computer-based tools (includes computer models, management flight simulators and learning laboratories) (Kim, 1990).

While model-based mapping and approach is inherent to all the methods listed above, energy system models can be classified as a category in their own right, going by their growing numbers and rapidly increasing popularity since the second half of the twentieth century. Their growing popularity and widespread application to energy systems transition study and analysis has been attributed to their ability to generate a range of insights and scenarios through feedbacks representing the complexity of interactions and capturing the exchanges between various layers of energy decision-making (Pfenninger et al. 2014).

**Energy System Models**

The emergence of energy systems as complex systems has been established in preceding sections. In its simplest sense, energy systems can be defined as ‘technical and economic systems meeting energy demand’, which in turn are influenced by ‘price, regulation and customer preferences’ (Groscurth, Bruckner & Kümmel, 1995:941). It can also be defined as the ‘process chain (or the subset of it) from the extraction of primary energy services to the use of final energy to supply services and goods’ (Pfenninger et al., 2014 c.f. Global Energy Assessment). It includes the aggregate processes of acquiring and using energy in an economy (Pfenninger et. al., 2014:76). Given the mesh of exchanges between and among multiple actors-producers, generators, suppliers, consumers and decision makers, who interact through interconnected physical and social networks of information and decision systems, governed by institutional and political structures on objectives that evolve constantly and often find various actors and decision makers in disagreement, a range of difficulties
are encountered in energy governance on account of limited cognitive capabilities impacting rational decision making in the light of emerging complexities in energy systems (Bale, et al., 2015). Complex systems thinking and approach is a valuable tool to understand the underlying interactions between components in energy systems that give rise to emergent system properties and the limited or ‘bounded’ rationality of those actors in relation to decision-making under uncertainty (ibid;pp:152). Because of how energy links the key problems and opportunities of the twenty-first century, much work has been undertaken for energy systems analysis, which has been extremely multidisciplinary, employing a range of methods that apply to various specific elements of energy systems.

Energy systems models first emerged in the wake of oil crisis in the 1970s, when policymakers and industry experts from major consumer states realized the need for long-term strategic planning to manage energy resources in a way that reduced the effect of after-shocks (or to be better prepared when such situations arose) (Danzig, 1965). Though some scholars, like Hoffman and Wood (1976), suggest that energy accounting approach, as a framework for energy system analysis, may have been in use in the US even in the 1950s.

Detailed comparative assessment of energy system models and methodologies can be found in a number of studies, including those by Jebaraj and Iniyan (2006) and Pfenninger et al. (2014). A broad summary of review literature reviewed on energy system models is presented in Table 2.3.

### Table 2.3: Review of Literature on Energy System Models

<table>
<thead>
<tr>
<th>Publication</th>
<th>Focus</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoffmann and Wood, 1976</td>
<td>Provides an introduction to the scope, applications, methodology, and content of energy system models, particularly those developed and used in the U.S.</td>
<td>Provides introduction to the scope, applications, methodology of energy system models developed and used in the United States.</td>
</tr>
<tr>
<td>Choucri, 1979</td>
<td>Review of World Oil Market Models to highlight the characteristic features of price determination in models of the world petroleum market</td>
<td>Compares the structure of 12 world oil market models (both optimization as well as simulation models)</td>
</tr>
<tr>
<td>Jebaraj and Iniyan, 2006</td>
<td>To understand and review various emerging issues related to energy modelling</td>
<td>Energy-planning models; Energy supply-demand models; Forecasting models; Optimisation models; Energy models based on neural networks; Emission reduction models</td>
</tr>
<tr>
<td>Al-Oahtani, Balistreri and Dahl, 2008</td>
<td>Reviews various oil market simulation and optimization models; and the literature on modelling, testing and analyzing OPEC’s behavior within the oil market</td>
<td>Oil market simulation and optimization modelling.</td>
</tr>
<tr>
<td>Bhattacharya and Timilsina, 2010</td>
<td>Comparative overview of energy system models, tracing their origin and assessing their suitability for addressing challenges specific to the context of developing countries</td>
<td>Bottom-up optimization (EFOM, MARKAL, etc.); Bottom-up accounting (LEAP); Top-down econometric; Hybrid models (POLES, WEM); Electricity planning (WASP, EGEAS)</td>
</tr>
<tr>
<td>Pfenninger et. al., 2014</td>
<td>Reviews models relevant to national and international energy policy against four modellings paradigms and analyses challenges prevalent in each while also elaborating on efforts being undertaken to address them.</td>
<td>Energy system optimization models; Energy system simulation models; Power system and electricity market models; Qualitative and mixed-methods scenarios; Emerging approaches including examples of energy systems modelling in the UK</td>
</tr>
</tbody>
</table>

To depict a given system, models may use ‘technical, environmental and social elements’ (ibid:76). These models can then be formulated using theoretical and analytical methods, drawn from various disciplines like engineering, social sciences, economics, operation and behavioural research etc.,
using a range of techniques like linear programming, econometrics and methods of statistical analysis (Hoffman & Wood; 1976). Each resulting model can, therefore, be unique depending on the chosen attributes and parameters.

Energy systems models can be employed for both ‘normative analysis’ (where the purpose is to measure the impact of some exogenous or independent changing element or process on the system) as well as for predictive purposes (for example, to forecast energy supply and/or demand over a time frame). Models based upon economic theory emphasize behavioural characteristics of decisions to produce and/or utilize energy, while the technical aspects of these processes can be derived from models that are based in engineering concepts. While behavioural models are usually oriented toward forecasting uses, the process models tend to be more normative (ibid: 10-15).

Some studies categorise models based on their types, such as: energy planning models; energy supply-demand models; forecasting models; renewable energy models; emission reduction models; optimization models; and, neural network and fuzzy logic models (Jebaraj & Iniyan; 2004). Other studies, on the other hand, categorize them under different paradigms such as: optimization models; simulation models; qualitative or mixed-scenario models (Pfenninger et al., 2014). Van Beeck’s taxonomy of energy models is different from those described above and is based on: general and specific purposes of energy models; model structure; analytical approach: top-down vs. bottom-up; underlying methodology; mathematical approach; geographical coverage; sectoral coverage; time horizon, and finally, data requirements (2000:1-26). A broad categorization of energy system modelling methods is presented in Table 2.4. While studies vary in their classification of energy models, the basic tenets are roughly similar.

Table 2.4: Energy Models Methods and Techniques

<table>
<thead>
<tr>
<th>Methods and Technique</th>
<th>Application</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear programming and dynamic programming</td>
<td>Capacity-expansion and energy-economy analysis</td>
<td>WASP model (Foel, 1985); MARKAL (Fishbone &amp; Abilock, 1981); RES Model (Howells et al., 2011)</td>
</tr>
<tr>
<td>Mixed-integer linear program</td>
<td>Optimisation of distributed energy resources system</td>
<td>MILP model (Omu et al., 2013)</td>
</tr>
<tr>
<td>Econometric methods</td>
<td>Energy Outlook; To analyse the role of Carbon Capture and Storage (CCS)</td>
<td>NEMS model (Kydes and Shah, 1997); SGM model (Praetorius and Schumacher, 2009)</td>
</tr>
<tr>
<td>Partial equilibrium model</td>
<td>Development of US Climate Action Plan</td>
<td>IDEAS model (Wood and Geinzer, 1997)</td>
</tr>
<tr>
<td>Optimization</td>
<td>Optimisation for CO₂ control</td>
<td>Islas and Grande’s model (2007)</td>
</tr>
<tr>
<td>Scenario analysis</td>
<td>Analysis of energy policies</td>
<td>Munasinghe and Meier’s Model (1993)</td>
</tr>
<tr>
<td>Agent-based modeling</td>
<td>Quantitatively support climate policy formulation and evaluation</td>
<td>ENGAGE model by Wang et al. (2013)</td>
</tr>
</tbody>
</table>

Source: Adapted from Qudrat-Ullah (2015:7-8)

Despite the availability of a wide range of energy systems model, care must be taken in selecting the modelling approach and method, as not all methods and techniques apply equally to all the studies. Target-group, intended scope and nature of enquiry, desired geographical coverage, conceptual framework, available information are all significant determining factors (Herbst et al., 2012:113).
A more general way to classify energy system modelling approach is as top-down or bottom-up approach. Detailed description of top-down [and bottom-up] models exist in a number of studies (Chapter 8, IPCC, 1996a; Frei et al. 2003; Jebraj and Iniyan, 2006; Al-Qahtani, Balistreri and Dahl, 2008; Böhringer and Rutherford, 2008; Bhattacharya and Timilsina, 2010). Based on the classification provided by Pfenninger et. al. (2014.) and Herbst et al. (2012) a schematic of energy system modelling approach is provided in Figure 2.1.

While top-down models present an aggregate representation of the systems being analysed, bottom-up models are associated with higher degree of details associated with them. Top-down energy models, for example, may represent the economy as a whole, simulating future demand and supply for various sectors and mapping their impact on various economic indicators (like employment, foreign trade, etc.).

---

Figure 2.2: Energy Modelling Approaches

Source: Based on Herbst et al., 2012:112-123 and & Pfenninger et. al. (2014)

Structural changes in the economy, markets, geopolitical movements, price shifts etc. drive top-down models, which uses feedback loops between various constituents of wider system to assess their impacts. Top-down models, as shown in Figure 2.2, can be further categorized as: input-output
models; econometric models; computable general equilibrium models and system dynamics (Herbst et al.; 2012). Models from the bottom-up family prove useful in understanding details of supply and demand patterns as well as their plausible futures. These lend very well to detailed policy analyses. However, their use is severely limited as they often require large-scale simplifications for keeping the model within manageable bounds (Herbst et al., 2012). Partial equilibrium, optimisation, simulation and multi-agent models belong within the bottom-up category. Partial equilibrium models do not focus on inter-sectoral linkages or system-wide impacts on the economy and can therefore include more technological details, but they struggle in balancing model resolution with data availability. These models have to be kept coarse (spatially and temporally) to retain solvability. With fluctuating market trends in current energy system, there is now a greater need than ever to actively manage variable demand-supply trends and resolving space and time, which becomes vital for answering specific questions related to supply-demand fluctuations (Pfenninger et al., 2014:76-77).

It becomes clear that the high complexity and dimensionality of issues associated with energy systems, cannot be addressed by optimization techniques alone, which focus on optimization of specific variables for a system. Most modelling approaches described thus far do not address concerns over uncertainty and abstract away from reality. Many studies suggest the use of deterministic and stochastic methods for dealing with aleatory uncertainty, which includes: probabilistic approach (like point-estimate method, Monte Carlo Simulations, scenario based decision making), possibilistic approach (employing fuzzy set theory), hybrid possibilistic–probabilistic approaches (like possibilistic-Monte Carlo approach and possibilistic-scenario based approach), information gap decision theory, robust optimization and interval analysis (Soroudi & Amraee, 2013:378-383). Although these models do certainly provide more details, are much more deterministic, they do not offer a complete representation of real-world systems.

**Evaluating Dynamic Complexity: Agent-Based or System Dynamics Approach?**

Several studies (Haydt et al., 2011; Glassmire at al., 2012; Matthew et al. 2015, 2017) support the need for temporal and spatial resolution through high-resolution models. Multi-agent models simulate the dynamics of complex adaptive systems comprising of interacting agents. By modelling all the agents and their behaviours by assigning specific set of rules, systemic-behavioral patterns can be observed and patterns that arise out of interactions of agents can be explained, which, in turn, can be used to improve the overall environment within which various systems operate (Macal and North; 2010:151-162). Agent-based simulations and system dynamics are two most commonly used approaches for investigating complexity in energy systems, each with their specific advantages and disadvantages depending on the scope and nature of enquiry (Ding, 2018).
System dynamics uses an aggregated top-down approach and agent-based modelling uses a highly disaggregated bottom-up approach. Agent-based simulation is helpful where spatial interactions are important and need to be closely considered. Because of the inability of agent-based simulation to consider social and economic factors, the method is not suitable for studies that need to take a holistic-thinking perspective, such as in this PhD research. A comparison between agent-based and system dynamics modelling methods is provided in Table 2.5. While agent-based models are important for improvements in decision-making and for testing alternative scenarios, their use is majorly limited by its ‘enormous demand on additional empirical data’ to simulate behaviors of all the agents in the system (Herbst et al.; 2012:124).

Table 2.5: Comparison between Agent-based Modelling and System Dynamics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Agent-based Modelling</th>
<th>System Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building blocks</td>
<td>Agents</td>
<td>Feedback loops</td>
</tr>
<tr>
<td>Unit of analysis</td>
<td>Rules</td>
<td>Structure</td>
</tr>
<tr>
<td>Level of modelling</td>
<td>Micro</td>
<td>Macro</td>
</tr>
<tr>
<td>Modelling paradigm</td>
<td>Bottom-up</td>
<td>Top-down</td>
</tr>
<tr>
<td>Handling on time</td>
<td>Discrete</td>
<td>Continuous</td>
</tr>
<tr>
<td>Mathematical formulation</td>
<td>Logic</td>
<td>Integral equation</td>
</tr>
<tr>
<td>Origin of behaviour over time</td>
<td>Events</td>
<td>Levels</td>
</tr>
<tr>
<td>Adaptation</td>
<td>Change of structure</td>
<td>Change of dominant structure</td>
</tr>
<tr>
<td>Software platform</td>
<td>NetLogic, Swarm, RePast, AnyLogic</td>
<td>Vensim (PLE and DSS), iThink, Stella</td>
</tr>
<tr>
<td>Process</td>
<td>Research Question→ Specification-Formalisation→ Modelling-Verification (implementation, verification, data analysis)→ Calibration &amp; Validation→ Model Use</td>
<td>Boundary determination and dynamic hypothesis→ Conceptualisation (stock and flow diagramming)→ Quantitative model (parameter value determination)→ Model Validation→ Model Use</td>
</tr>
</tbody>
</table>

Source: Based on Ding (2018)

System dynamics methodology, on the other hand, applies extremely well to the scholarship of complex systems given its ability to ‘address the fundamental structural causes of the long-term dynamic (meaning changing over time) contemporary socio-economic problems’ (Barlas, 2007). It helps to understand the structure responsible for causing a complex (and often) undesired behaviour. Emerging out of control theory and servomechanisms and grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering, system dynamics methodology applies equally well to human systems as it does to physical and technical issues (Sterman, 2000). Pioneered at MIT by Jay W. Forrester, system dynamics is a method that helps to develop and test formal mathematical models and computer simulation of complex dynamical systems and provides an understanding of dynamic complexity that gives rise to counterintuitive behaviour of complex systems emerging from feedback between agents over time. It combines the theory, methods, and philosophy needed to analyse the behaviour of complex...
systems and provides a common foundation that can be applied to understand and influence how things change over time.

System dynamics models adopt a feedback perspective and endogenous view (i.e. structure of a system drives its behaviour) to explain the dynamics of complex systems. For instance, fluctuations in oil price can be explained by analysing the internal factors and exchanges that take place between various supply and demand drivers in the system. The system dynamics pedagogic view maintains that a better understanding of internal structures will lead to a better understanding of outcomes, and as a corollary, modifying the structure responsible for undesired behaviour can avoid unwanted outcomes. Barlas posits that ‘understanding the causes of unwanted dynamics to design new policies to eliminate them’ is the main purpose of system dynamics methodology (2007:1133).

Many studies provide detailed expositions of major aspects of system dynamics methods and components (Sterman; 2000; Barlas; 2007; Mutungi et al.; 2017). According to Sterman, the behaviour of a system arises from ‘interactions between the physical and institutional structure of the system with decision-making processes of various agents that act within the system’ (2000:106). The basic modes of behaviour include growth (created by positive feedback); goal seeking behaviour (created by negative feedback); and oscillations (created by negative feedback with time delays), while non-linear interaction of the basic modes gives rise to more complex modes such as S-shaped growth and overshoot and collapse (ibid).

Within the framework of systems thinking paradigm identified through various definitions in Table 2.2 and the context of research outlined in the preceding sections, system dynamics provides an invaluable tool for understanding and engineering complex systems. Through its ability to facilitate holistic analysis, rather than focusing on just some constituent parts, system dynamics offers an important evaluation tool that closely matches the prerequisites for systems thinking (as laid out in the definition by Arnold & Wade (2017)): helping recognise interconnections; identifying and representing feedback; explaining system structure through stocks, flow and variables; depicting and capturing non-linear relationship and dynamic behaviour; and as a joint consequence of the foregoing modify incongruous behaviour of systems. In the context of policy making and governance the ‘persistent, chronic, recurring’ dynamic problems (characterised by variables that undergo significant changes over time) are of a systemic nature, ‘originating from complicated interactions between system variables’ (ibid: 1132). As highlighted by Snyder (2008), applying systems engineering to the desired transition to sustainable energy systems is crucial as it helps in the planning, development and implementation of innovative technologies in full consideration of the heterogeneous set of stakeholders involved across various stages of today’s energy systems.

Systems engineering, using system dynamics can help to evaluate the impact of policy decisions on
long-term energy pathways. The dynamic policy decisions, directed by rules, can manage (control, alter or reverse) the dynamic behaviour of systems; and different future scenarios can emerge from different sets of policy decisions.

System dynamics method has therefore been deemed suitable for generating the primary evidence base for this PhD research as it can help in assessing the impact of current policy choices on future pathways and in determining their efficacy in meeting the sought energy policy objectives.

Use of system dynamics models also helps energy governance scholarship is two interlinked ways: they explain the long-term outcome of the existing policies on energy systems in light of inherent nonlinearities and feedbacks, and in doing so, the model-based enquiry highlights the gaps that exists between the current system-driven and desired outcomes, and this, in turn, helps to assess the efficacy of existing governance framework in achieving the desired energy policy objectives.

Most analyses of policies are often restricted by data availability. System dynamics models in contrast require relatively less data. This puts system dynamics models at a greater advantage over econometric models where historical time series data is required for every variable to fit the model. A partial comparison between econometric and system dynamics models is presented in Table 2.6.

<table>
<thead>
<tr>
<th></th>
<th>Econometric Methods</th>
<th>Simulation through System Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>System boundary</td>
<td>These are open systems, including many factors that are relative to time horizon under consideration, not determined by the system modelled. Exogenous variables are needed to estimate the parameters of the model, with specific assumptions about their natures with restrictions on their use.</td>
<td>A system dynamics simulation seeks to represent a closed system and generate reasonable system behavior without recourse to exogenous variable. If all the key relationships are included in a feedback structure, then the behavior modelled will be adequately simulated.</td>
</tr>
<tr>
<td>Stochastic factors</td>
<td>Assumes that a simulation (or forecast) is not meaningful unless accompanied by a statement regarding level of uncertainty.</td>
<td>Assumes random factors are not strong enough to determine system behaviour.</td>
</tr>
<tr>
<td>Validation</td>
<td>Adopts a statistical perspective on validation independent of the purposes of the analyst.</td>
<td>Validation in system dynamics is defined not by external criteria but by the extent to which the model replicates historical behaviour and is useful in decision-making</td>
</tr>
<tr>
<td>Uses of data</td>
<td>Requires data to estimate the parameters and evaluate the validity of the model based on statistical requirements and constraints.</td>
<td>Emphasizes on specifying functional relations among variables rather than identifying their statistical relationships.</td>
</tr>
<tr>
<td>Reference mode</td>
<td>Parameters estimated empirically are used as the base case.</td>
<td>Defines system behavior in equilibrium as its basic reference.</td>
</tr>
<tr>
<td>Time frame</td>
<td>Adopts a short-range perspective, as the parameters estimated from empirical data are valid only over the data base period used.</td>
<td>Adopts a long-term perspective and can adapt to any time perspective with any time interval.</td>
</tr>
<tr>
<td>Feedbacks</td>
<td>Less dynamic, and less prone to feedback specification due to the nature of algorithms.</td>
<td>Are built into simulations by assumptions, algorithms, and functional specifications.</td>
</tr>
</tbody>
</table>

*Source: Based on Choucri and Heye (1990:366-367)*

Furthermore, system dynamics models also allow to formulate nonlinear relationships. Samuelson (1947; 288) maintains that it is because of the mathematical difficulties involved in nonlinear
systems that the economists have used linear systems for their queries. But nonlinear relationships, such as the impact of policy on chosen parameters, or the impact of social, economic, and political constraints on policy choices, are fundamental to complex systems (Sterman; 2000). System dynamics presents a practical and simple method for eliciting information about nonlinear relationships by simply specifying shapes and values of various nonlinear functions, drawing on from qualitative and quantitative data.

System dynamics for complex energy systems

As Dana Meadows (1991:3) put it:

... if we want to bring about the thoroughgoing restructuring of systems that is necessary to solve the world’s gravest problems ... the first step is thinking differently. Everybody thinking differently. The whole society thinking differently.

The quest to understand the dynamic complexity of the process of governance and policy change has been an ongoing one. Systems thinking plays a vital role in understanding and dealing with complex systems attributes of energy systems, identified in Table 2.1. Adopting a system thinking perspective lays a strong evidence-based foundation for engaging in and constructing coherent narratives and interpretation relating to system governance issues (Jaradat, 2015). A holistic systems approach can determine the degree of success in the development of governing systems that lead eventually to effective governance. Higher levels of system thinking are required for effectively addressing the twenty-first century challenges associated with energy systems that are characterised by increasing levels of complexity, ambiguity, emergence, and uncertainty. Jaradat (2015) posits that while systems thinking cannot be portrayed as a ‘panacea’ to address all the systemic challenges that may be afoot, it does ‘offer a compelling argument as a necessary, if not sufficient, condition to increase effectiveness in dealing with these problems and therefore successfully engage governance activities’ (pp:61).

Selecting the most effective governance approach (or tools for it) is a difficult task in complex systems. However, adopting a system thinking perspective provides key insights into relationship between sub-system components and understanding of changes needed in the system structure, which are crucial for designing systems that are flexible and capable of dealing with any unpredictable behaviours in complex systems (Jaradat, 2015). This explains the use of system dynamics models to analyse a number of complex energy policy related issues since the 1970s (Naill & Belanger, 1989). Naill applied this theory to the U.S. energy system and recognised that these were ‘undergoing a major transition away from the use of liquid and gas fuels towards a new mix of energy resources’ (1989, p. 424). Energy systems remain in transition even today, many decades
later, albeit this transition is more complex and interconnected than the previous transitions from (wood to coal (in the 1800s) and subsequently from coal to oil and natural gas in the twentieth century) with the challenges created by climate change (ibid).

**System Dynamics in Energy Policy Studies**

System Dynamics models have been widely used as a tool to study an energy system’s behaviour (Hosseini and Shakouri, 2005:67), and for designing policies through computer-aided modelling and simulation of complex situations. Understanding the dynamics of energy systems (mostly restricted by geography or resource type) has been the focus of, what is now over six decades of, system dynamics modelling effort, which began at the MIT in the early 1970s, and was carried forward at the U.S. Department of Energy (with an objective of developing an integrated model of energy supply and demand in the U.S.) (Naill & Belanger, 1989). This effort was directed at preparing projections for energy policy analysis in the U.S., using the life-cycle theory of M. King Hubbert (Hubbert, 1950) which stated that depletable resources (such as oil and gas) must follow a life-cycle whereby a period of low prices will lead to growth in production, leading to drop in discoveries as a result of resource depletion, raising the prices and eventually resulting in a decline in production (Halbe & Pahl-Wostl, 2019).

In 1970, Jay Forrester created the first draft of a system dynamics model of the world’s socioeconomic system, which he called WORLD1 and later refined it to WORLD2 and published in a book titled World Dynamics, which was severely criticized but widely circulated. The model showed a collapse of the world socioeconomic system sometime during the twenty-first century, if steps were not taken to lessen the demands on the earth’s carrying capacity. The model was also used to identify policy changes capable of moving the global system to a fairly high-quality state that is sustainable far into the future. With the support of the Club of Rome, Dennis Meadow and his associates created the WORLD3 model and published in a book titled The Limits to Growth. In 1991, three of the original authors of the book redid the study and published the results in a book titled Beyond the Limits (System Dynamics Society).

The central assumption underlying the WORLD models was that the earth’s natural resources are finite and that the exponential growth in their use could ultimately lead to their depletion and ultimately an overshoot and collapse of the world socioeconomic system (Eastin et al., 2010; Myrtevit, 2005). Such an uncontrolled economic and population growth, claimed the report, would bring about ‘a sudden and uncontrollable decline in both population and industrial capacity’ within the next 100 years (Meadows, 1972). These claims were, however, mitigated by market-led innovations and countered severely by proponents of ‘growth-as-usual’ (Beckerman, 1972).
publication of Limits to Growth report was met with severe criticism, with economic communities criticizing the ideas in the report as dooms day prophecy and not based on observed data or established theories. Many authors also criticised the unsuitability of the method and rubbished most of the results published in the book. Extensive debates in academic circles and coverage in press (The Economist, Newsweek, The New York Times) followed (Eastin et al., 2010). A detailed scientific enquiry into various facets of the controversy related to The World Models has been carried out by Myrtveit (2005) and Eastin et al. (2010).

System dynamics, has since, grown slowly, but surely and has been successfully applied to an array of problems. Some of the early applications of system dynamics in energy modelling include Roger Nail's FOSSIL2 model, which was an integrated model of U.S. energy supply and demand used to inform its policies in the 1970s and 1980s (Nail, 1992). Extensive improvements were made to FOSSIL2 model and the improved model was called IDEAS (Improved Dynamic Energy Analysis Simulation) model maintained by United States Department of Energy (USDOE). The missing feedback between energy sector and economy was captured in John Sterman's Model of Energy-Economy Interactions (Sterman, 1982). A noteworthy addition to modelling effort was brought about through Fiddaman's work, which also included a critique of existing (non system dynamics) climate-economy models alongside a new climate-economy system dynamics model called FREE (Feedback-Rich Energy Economy model) was developed. The FREE model explicitly incorporated the dynamics of oil and gas depletion as a "source constraint" on the energy-economy system (like its system dynamics predecessors), as well as the dynamics of a "sink constraint" (i.e., climate change) on the energy-economy system. The FREE model was the first energy-economy model to examine the impact of source constraint on energy-economy interactions.

System Dynamics modelling has proved particularly significant in studies that include cross-cutting implications from socio-economic, political, management, market and environmental domains (Choucri et al., 2007:3-4). It has been used to analyse dynamic relationship of energy and the economy (Sterman, 1981), to modelling world petroleum market over several decades (Choucri, 1981; Morecroft & Heijden, 1990, 1991), to study the long-term dynamic behavior of oil and gas exploration industry (Choudhary & Sahu, 1992), to mapping the future of resource development under different price scenarios (Hosseini and Shakouri, 2005; Samii & Teekasap:2009). System dynamics has also been applied to analyse the regional and global market impacts on policy dynamics (Kiani & Pourfakhraei, 2010; and various). With an extensive use and application in climate change vulnerability assessment (see Fiddaman, 2002; Sterman et al., 2012; Füssel & Klein, 2006), system dynamics modelling has now been used for strategic energy planning and policy analysis for over half a century.
Despite the use and application of system dynamics models for over five decades in energy policy domain, some scholars think that its use by political scientists to utilise systems thinking has been rather limited. In a study titled *Approaching a Model of Policy Change: A Challenge to Political Science*, Rissmiller (2000) suggests that there could be several ways in which the use of system dynamics can enrich the existing models in policy making. The author points out that systems analysis continues to remain one of a ‘handful of primary approaches’ in the study of public policy but is hardly used by political scientists because very few political and social scientists are trained in system dynamics. The author also maintains that while system dynamics is a thriving field, its use as a systems-thinking tools in academic political science and governance is largely dormant. However, there is evidence suggesting use of system dynamics in policy making and analysis. Lave and March used diffusion models in *An Introduction to Models in Social Sciences* (1975) and Stockey and Zechauser used stock and flow model in their widely cited study *A Primer for Policy Analysis* (1978). Chouchri used the theory of lateral pressure, which refers to the propensity for extension of behaviours outside territorial boundaries, and modelled it explicitly using a system-dynamics model and used the results to contribute to the existing theory as well as to provide seeds for policy thought (Chouchri, 1998).

**System Dynamics Modelling Process**

The system dynamics modelling process starts with the definition of a dynamic problem (or, dynamic hypothesis of the problem) and takes place in the context of real-world problem solving, with its latent ambiguities, delays, socio-economic and political context, and conflicting policy priorities (Sterman, 2012). The simulation model replicates the structure of the system in question and reveals the behavioural implications of the system described by the model. System dynamics enables to
dynamically model the long-term effects of policies and helps in identifying sensitive policy leverage points in the system. Feedback structures are defined such that existing conditions lead to decisions that result in changes in surrounding conditions which in turn impacts subsequent decision. In complex systems these decision-making structures are intertwined and interconnected through long cascades chains of actions, where each part is constantly reacting to their own decisions as well as to those of others (Forrester, 1992). System dynamics helps move beyond the open-world unidirectional mental models that are static, narrow and reductionist and factor in elements of dynamic complexity such as feedbacks, time delays stocks and flows. It presents the feedback view of world where actions often trigger unanticipated consequences. Furthermore, cause and effect in complex systems are often distant in time and space, and the delayed consequence of our actions are either different from or less noticeable than their immediate effects (Sterman, 2002).

Another important feature of system dynamics models is the ability to capture the effect of time delays between taking a decision and its effect on the state of the system. Delays are important real-world phenomenon that significantly impact the behaviour of systems by reducing our ability to accumulate experience, test hypotheses and learn (Sterman, 2002). Simulation conducted in the virtual world inform the design and implementation of policies in the real world; experience in the real world then leads to improvements in the mental models.

As an analysis tool, system dynamics allows to both describe the relationship between variables as well as represent a problem (Sterman, 2000). Inputs in a system dynamics methodology are generated from feedback relations within the system, and the outputs of one period feed in as inputs for next. Because the inputs are generated endogenously, their behaviour is state determined.

Stock and flow notation provides a general way to graphically characterize any system process. They characterize the state of the system and generate the information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in systems. Stocks are represented by rectangles, and can be used to depict both material and nonmaterial accumulations. Flows are used to depict activities. Delays in a system represent lags, which can effectively enhance or dampen the stability of the system and usually explains why it often takes time for the effect of policy decisions to be felt. They determine the severity of ‘shocks’ and are responsible for the ‘overshoot and collapse’ behaviour demonstrated by many systems (ibid). In Sterman’s words, the art of system dynamics modelling is discovering and representing feedback processes, together with stock and
flow structures, timedelays and nonlinearities. A simple stock and flow diagram is presented in Figure 2.3.

![Simple Stock and Flow Diagram](Image)

**Figure 2.3 A simple stock and flow diagram in System Dynamics**

The system dynamics modelling process follows along the following lines: problem articulation (selecting the theme, time horizon and reference modes); formulation of dynamics hypothesis (initial hypothesis, mental models and causal loop diagram, stock and flow maps, etc.); formulation of a simulation model (specification of structure and estimation of parameters); model testing (comparison to reference modes, robustness under extreme conditions, sensitivity, etc.); and finally policy evaluation (scenario specification, policy design, etc.). Figure 2.4 presents an overview of the modelling methodology in system dynamics. When an element of a system indirectly influence itself, the portion of the system involved is called a feedback loop. A map of the feedback structure of a simple system is a starting point for analysing what is causing a particular pattern of behaviour.

![System Dynamics Methodology](Image)

**Figure 2.4: System Dynamics Methodology**
*Adapted from Aslani, Helo, and Naaranoja, (2014)*

The central premise around which the methodology is based is that structure of a system determines its behaviour. The theory of dynamic systems adopts a state variable approach. The only way stocks can change is via its inflows and outflows. Systems consist of networks of stocks and flows linked by feedbacks between stocks to the flows (or rates). All dynamics in systems arise from the feedback between positive and negative loops. These may interact in a number of ways to generate dynamic patterns that can take the form of growth, decay, or oscillations.
Six basic archetypes in system dynamics are: \textit{exponential growth, exponential decay, s-shaped growth, overshoot and oscillations}. General patterns of system behaviour associated with each of the six system archetypes are presented in Figure 2.5, where R denotes \textit{reinforcing behaviour} and B denotes \textit{balancing behaviour}. Exponential growth is one of the most pervasive dynamics. It is caused when the system doubles in size in a fixed time. Exponential decay is the inverse of exponential growth and occurs when a system loses half its value in fixed time. In cases where a system decays, but not all the way to 0, exponential approach can be observed. S-shaped growth occurs when the system initially grows exponentially, but as it grows large and large it encounters limitations, and reaches equilibrium.

If an S-shaped system does not encounter smooth accommodation but encounters delays in the reaction to its limits, the system encounters an overshoot. Oscillations occur when delays take place in balancing feedbacks. These dynamic patterns help in identifying the inherent structures that are responsible for their behaviour patterns. System dynamics presents a set of tools that can help identify, depict, and analyse multiloop non-linear feedback relationships and applies extremely well to the current research.

\textbf{Figure 2.5: General patterns of system behaviour}

\textbf{Model Validation in System Dynamics}: A model is essentially a representation of ‘cause and effect mechanisms operating in the system’, analysed using computer-aided representation and compared against the known behaviour. The adequacy of this representation must be tested across all its aspects including the mathematical formulation and the interpretation of its output (Fishwick, 2007:28). Model validation has been defined as a confidence building process with respect to its purpose (Forrester, 1960; Barlas, 1994). It is a crucial step in system dynamics as it adopts a unique evaluation criterion for energy systems model and by doing so increases the confidence in its
Establishing structural and behavioural validity of models is an important indication of their goodness-of-fit and ascertain the degree of confidence on the inferences they generate (Qudrat-Ullah, 2008:575). While a good modelling practice entails checking model validation at each step (as shown in the testing process in Figure 2.6), in establishing the appropriateness of its structure is critically important. Upon successfully validating a model’s structure, model’s behavioural validity is established, proceeding iteratively between these aspects (Qudrat-Ullah & Seong, 2010:2217). The reason behind testing the structural and behavioural validity stems from the basic assumptions upon which the foundation of most system dynamics models is based: structure derives behaviour and that a model must fulfil a specific purpose (ibid c.f. Forrester, 1961).

The models produced by this research will be validated both structurally and behaviourally so that the conclusions drawn can be evaluated and taken forward with confidence. The model development process in this PhD research begins with the conceptualisation of the policy problem. This is determined through a thorough analysis of the theory and by reviewing the data on trends and outlook.

A model that captures the recent trends in global oil exchanges and impact of continued coal consumption in India on its emission reduction ambitions and analyses suitable dynamic pathways into the future was not found. Nail’s COAL, COAL1, FOSSILS models were some of the earliest efforts to use system dynamics to design and analyse US energy policy. Extensive efforts to study aspects related to oil were undertaken in the wake of oil crises in the 1970s and the 1980s. Choucri et al. (1992) studied the Egypt’s oil industry as a near-typical, non-OPEC oil producing country. Many other
popular models of energy, significantly of coal and oil, were developed by researchers over the years, including by Sterman (1980), Fiddaman (1997), Ford (1997) (also table 2.7). However, the world today is much different from the world in the 1990s or the early 2000s. A number of structural changes have occurred in the energy policy space. The architecture of energy system is different from what existed in the past; and as enshrined by the SD principle - structure determines behaviour, the behaviour generated by these new structures will be different. This creates a huge gap in the literature, which the PhD research aims to bridge by providing model-based analyses into the policy scenarios that may arise as a result of recent changes in policy and market dynamics.

This study aims to analyse new behaviours and challenges arising from the changing market and policy directions in the energy sector. As outlined in the previous sections, models of global oil exchanges and Indian coal and renewable energy-based power generation system are developed in this PhD research. While price formations are central to the dynamic behaviour of both oil and coal dynamics, oil markets globally are well established and mature; coal prices in India, on the other hand, are mostly strategically controlled by the Government. Mapping the scenarios and implication of changes in policy direction arising as a result of feedbacks between various policy objectives in India and its wider impacts on emission pathways is considered more relevant. Adequate boundaries are set based on the literature review and ascertaining various parameters relevant to this work. The causal relationships are developed based on the knowledge of the systems gathered by reviewing the literature. After verifying the structure through relevant causal loop diagram, a mathematical model is created, ensuring dimensional consistency and verification of parameters at each stage. This resulting operational model is suitably subjected to extreme conditions test and structurally oriented behaviour test. To test for dimensional consistency, measurement units for each mathematical equation in the model are carefully checked for consistency. Data of real systems will be gathered from credible sources like the IEA, the U.S. Energy Information Administration, the BP statistical review and other country specific websites, etc. The model will also be tested to analyse its behaviour when extreme values are assigned to some of the selected parameters. The behaviour generated will then be analysed against that of the real system.

The software that is currently used is Vensim version 8.0, developed by Ventana Systems Inc. Vensim organises itself around models and data or simulation of these model. Because Vensim maintains a clear distinction between the structure and the behaviour of the model it will be very useful for testing the validity of model. Vensim scores over other available system dynamics softwares (like STELLA, I Think, Powersim) due to the Reality Check® feature available in Vensim. Reality Check® ensures that the theoretical equations used stay within the boundaries of reality; allow the modellers to have confidence in the quality of the results; the equations are statements
about the nature of behaviour in reality which do not require a separate structure for generating the chosen behaviour.

**Scenarios for Future Thinking and Foresight**

One significant way in which system dynamics method can enrich governance processes is through the scenarios these models generate. The biggest challenge facing long-term planning is on account of uncertainty. Scenarios are descriptions of different possible futures (Chermack et al., 2001) and these are extremely helpful for governance reform as they capture the complexity emerging through interaction between various layers of energy decision-making process across time and space.

Scenarios developed by the SD models brings about an appreciation of the role of interacting sub-systems and their impact on the longer-term dynamics and pathways and can, therefore, help in modifying and correcting the variables that adversely impact the sought objectives. These scenarios cover the likely views of the future. System structures can be appropriately modified to achieve the desired ambitions and objectives. Alternatively, suitable advice can be made available based on the scenarios to alter the current policies, where possible, to avoid adverse impacts and prevent policy failures.

**Analysing uncertainty, ambiguity and variability using @Risk**

Energy systems transition is characterised by a high level of risk and uncertainty, resulting from high sensitivity to uncertain parameters such as fuel costs, market regulation and economic growth (Santos, Ferreira, & Araújo, 2015). Monte Carlo simulation is a computerised mathematical technique that allows to account for risk in quantitative analysis and decision making. It provides a range of possible outcomes and the probabilities they will occur for any choice of action.

The use of Monte Carlo simulation in this thesis is restricted to assessing the risk-reward analysis associated with the use of advanced-coal technologies for India’s power generation. Using @RISK software, Monte Carlo simulation was used for risk analysis by building simple models of possible results by substituting a range of values (determined through analysis of electricity tariff guidelines issued by India’s electricity board) with a probability distribution for any parameter that has inherent uncertainty. Depending upon the number of uncertainties and the ranges specified for them, a distribution of possible outcome values is generated. An illustrative summary of various methods used in this thesis is provided in Figure 2.7.
Summary:

This chapter establishes that energy systems have acquired the characteristics of complex systems. Recognizing the importance for holistic insights for successful and effective governance in the context of energy systems decarbonisation, a mixed-methods approach using both quantitative and qualitative methods enable to capture diverse perspectives to explore the key relationships and feedbacks that will be critical for future energy system transition. Document analysis enables to both set the conceptual framework for this thesis as well as to evaluate it against key feedbacks. Systems thinking concepts and tools helps to uncover how changes in specific parts of the system elements impact the overall system behaviour and thus have much to contribute in responding to the twenty-first century challenges of deepening energy system complexity.

Complex systems thinking and approach is a valuable tool to understand the underlying interactions between components in energy systems. Energy system models help to capture the complexity of energy systems and have been proven effective as a framework for energy system analysis. The chapter examines a wide category of energy system modelling methods, techniques and approaches and identifies system dynamics, which uses an aggregated top-down approach as the most suited method for this PhD research. System dynamics method addresses the fundamental structural causes of the long-term dynamic contemporary socio-economic problems and helps to understand the structure responsible for causing a complex undesired behaviour. Modelling approach and method associated with system dynamics is also outlined.
This research demonstrates the suitability of a mixed method approach using qualitative governance with complex systems thinking. The holistic combination of both qualitative governance with quantitative systems represents a methodological innovation in energy studies.

Next chapter provides relevant theories related to governance and global energy governance. Changes in energy governance paradigms and the existing arrangements of global energy governance are evaluated to assess how the relevant arrangements and processes associated with energy systems governance have changed over time.
Chapter 3: Global Energy Governance in the 21st Century: Perspectives, Paradigms, Objectives and Architecture

Overview

Issues related to the provision of energy services and deployment of energy technologies ensuring sustainability, security and affordability of supplies criss-cross a range of pressing global problems across geopolitical, environmental, economic and socio-political domains. The unprecedented transition to zero-carbon pathways is estimated to require investments in the range of $1 and $3 trillion per year for the next several decades (IEA, 2009; IMF, 2019). The scale of this challenge becomes even more daunting given our continued reliance on fossil fuels, which fulfil almost three-quarters of our energy needs, and stands for almost 70 percent of aggregate GHG emissions (IPCC, 2007).

Energy systems, and the externalities they create, are inherently interconnected and global in nature. Given the sheer scale and interconnectedness of challenges that need addressing urgently and simultaneously, effective governance of energy requires forward-looking and evidence-based policies, which can strike a delicate balance between various parts of this challenge and a coherent framework for the policy processes to function. And yet energy continues to be governed through siloed policies with limited reach and through a mix of standalone mandates tailored towards aiding the government of the land in meeting their respective agenda such as on climate governance, growth, social welfare, economic development, or other relevant issues as applicable. Energy markets, where they exist, have struggled to regulate price signals in the face of continued intervention by national policies impacting the supply and demand of commodities. Given the role of energy resources in driving growth and development, while regional governments strive to ensure energy security and reduced dependence, where practically feasible, remarkably less success has been achieved in other key aspects more specifically in climate change. All these together clearly symbolise the failure of governance mechanisms across all levels of decision-making strata in the energy governance framework and a need for substantial changes in the governance of global energy systems. The urgency to reform the governance framework and mechanism exacerbates as timelines to undertake a total shift to the Net-Zero economy become narrower.

Over the last two decades, energy governance has emerged as a major field of enquiry drawing scholars from many different backgrounds and interests. These scholars are broadly united in their quest to unravel the processes, frameworks, actors, and agendas that underlie the governance of energy globally. Through their endeavours, they enrich our understanding of central theories and
concepts that have historically dominated and framed the perspectives through which energy is analysed, often broadening the inherent boundaries, and including concepts from other fields to aid the process. With issues around energy transition gaining popularity in public discourse and across national and international policy agenda, this growing volume of research also helps to identify the glaring gaps and the remarkable ineffectiveness of the existing framework of governance in addressing the transnational issues surrounding energy system transition towards its desired objectives, most notably deep decarbonisation and Net Zero objectives. While scholarly work in international relations, global policy, systems and physical sciences address a number of energy governance issues, a majority of these continue to adopt a reductionist approach analysing only individual aspects of global energy governance in isolation with each other.

Much of the incoherence observed in global energy governance is also reflected in the existing literature. It is striking that for decades little attention was given to the inability of the institutional infrastructure deemed responsible for governing energy in addressing the challenges it faces (FLORINI & SOVACOOL, 2009). Existing accounts fail to acknowledge the complex dynamics of systems, such as their inherent tendency of path-dependency, lock-in, etc., that further challenge a successful transition towards wider energy objectives (Bale et al., 2015). Despite some specific enquiries into technological aspects of energy systems and effectiveness of energy market, or its failure, or policy decisions, a holistic approach from a global context is often not taken into account. These knowledge gaps serve as a key motivation behind this research.

This research contends that the energy governance framework needs to be examined more closely to assess its effectiveness in addressing the likely scenarios that are set to emerge from the feedbacks between policies and energy systems. An overview of various key aspects related to the theoretical construct for energy governance and global energy governance scholarship is provided in the following sections. A comprehensive review of the existing literature on governance, energy governance, global energy governance, transition management and paradigm shift theory is conducted using a very broad repository of literature.

The scholarly origins of governance theory

Coined first by Sydney Low in *The Governance of England* and originating from a Greek word *kybernan* (later translated as *gubernare* in Latin) meaning ‘to steer’, governance is used to describe the interrelationships between the changing nature of state, society and concerned with creating conditions needed for orderly rule and collective actions (Stocker, 1998).

The concept of governance, somewhat broadly, refers to the structures and processes that are instated to enable or prescribe how stakeholders interact among themselves in a manner that
ensures accountability, transparency, rule of law, stability, inclusiveness or simply towards the attainment of commonly agreed objectives. Rosenau and Czempiel argue that the main difference between “government” and “governance” is that the former exercises formal authority, backed by strong enforcement mechanisms, whereas the latter refers to activities backed by shared goals that may or may not rely on formal authority and coercive power (Rosenau & Czempiel, 1992). While often used interchangeably, government is just one of the many ways used for governance, which covers but goes beyond the functions of government to include the agenda-setting, negotiation, regulatory, implementation, and monitoring roles that are sometimes played by businesses or civil society actors (Florini, 2008). ‘Global governance’ encompasses the wide range of global issues that impact and involve multiple states and actors from various parts of the world, including the work of intergovernmental organizations established by governments (ibid).

Although an overwhelmingly large majority of researchers, particularly those ascribing to the principles of international relations (IR), public policy and international political economy, focus primarily on what governments do, there is a thriving community of researchers who address governance as a process that occurs outside of the formal bounds of government structures (FLORINI & SOVACOOL, 2009). Levi-Faur suggests that while being in existence in the scholarly margins since the 1950s, the notion of governance played a very limited role until the publication of Transaction Costs Economics: Governance of Contractual Relations by Oliver Williamson (1979), which marked the beginning of growing interest in the issues of economics of governance and corporate governance (Levi-Faur, 2012). Despite drawing attention to some of the issues around the new institutional economics around the notion of “transaction costs”, Williamson’s article only marginally examines the concept of governance. It was Rod Rhodes’ work “Policy networks: A British Perspective” (1990) that set out the agenda for much of the subsequent work on governance, evolving from the notion of network as a governance structure and an institutional arrangement with an informal sphere of authority. According to Rhodes:

...governance signifies a change in the meaning of government, referring to new processes of governing; or changed conditions of ordered rule; or new methods by which society is governed. (Rhodes R., 1996, p. 652)

He further maintains that the term governance:

‘...is broader than government, and covers non-state actors; includes continuous interactions between network members mediated by the need to exchange resources and negotiate shared purposes; it is characterised by game-like interactions, rooted in trust and regulated by rules of the game negotiated and agreed by network participants; contains a certain
degree of autonomy from the state, in that they are not accountable to the state but are self-organising; can be indirectly and imperfectly steered by the state’ (Rhodes, 2007:4).

**Governance as structure, process, mechanism and strategy**

A number of scholarly perspectives to elaborating the meaning of governance exist (Bevir, 2011; Jessop, 1994; Peters, 1994; Rhodes R., 1994, Rhodes R., 1997; Rhodes R., 2007). More generally, four different meanings are seen attributed to governance in the literature: a structure, a process, a mechanism and a strategy. A distinction between the *structure, process, mechanism* and *strategy* of governance is deemed important for analytical and theoretical purposes and is provided in some detail by Levi-Flaur (2012) (also Jessop, 2011; Boartolini, 2011) and is presented in Table 3.1.

**Table 3.1 Meaning and description of Governance**

<table>
<thead>
<tr>
<th>Governance Meaning</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>As a <em>structure</em>, governance signifies the architecture of formal and informal institutions and includes a range and “multi-level mix of institutional, socio-economic, ideational parameters” to denote a wide range of ways through which governance function is carried out across various approaches that allow the “study of alternative institutions of government (such as networks, markets, etc.).”</td>
</tr>
<tr>
<td>Process</td>
<td>As a <em>process</em> governance signifies the dynamics and the iterative aspects of steering functions involved in policymaking.</td>
</tr>
<tr>
<td>Mechanism</td>
<td>As a <em>mechanism</em> governance signifies institutional procedures of decision-making, of compliance, and of control, and can proceed via one of five main forms: monetized exchange, non-monetized exchange, command, persuasion and solidarity.</td>
</tr>
<tr>
<td>Strategy</td>
<td>As a <em>strategy</em> governance signifies the efforts by actors to govern and reform the design of institutional and procedural framework by relevant actors to “shape choice and preferences” (Levi-Faur, 2012 c.f. Barkay, 2009). <em>Governancing</em> refers to governance-in-action that go beyond the formal, more centralised ways of working by governments towards more decentralised and collaborative ways of governance.</td>
</tr>
</tbody>
</table>

Source: Levi-Faur (2012)

Whatever the structure, process, mechanism or strategy, governance can be defined more generally as a new cooperative mode of governing towards an agreed agenda where state and non-state actors participate in mixed public-private networks (Mayntz, 2004).

**Governance Paradigm Shift Theory**

Levi-Faur (2012) attributes the growing popularity of governance to the notion of change it signifies. This happens over a period of turbulence and therefore it is not surprising that scholars started to devote more and more attention to the study of change. Citing from Rhodes:

*Governance signifies a change in the meaning of government, referring to new processes of governing; or changed conditions of ordered rule; or new methods by which society is governed* (Rhodes, 1996:652).

Studies on ‘shifts’ in governance suggests that ‘authorities can be institutionalised in different spheres, which in turn can compete, bargain, or coordinate with one another’ (Levi-Faur, 2012). According to Levi-Faur (2012), based on the needs and drivers of change, shifts can occur in three
directions: upward (to the regional, transnational, intergovernmental, and global); downward (to the local, regional, and the metropolitan); or horizontally (to private and civil spheres of authority).

Some prominent examples of governance shifts include shifts from ‘politics to markets; from bureaucracy to regulocracy; from the positive state to the regulatory state; from the national to the regional and back to the global’ (ibid).

Scholars from different aspects of the political order have used specific parameters to evaluate shifts in governance, which in many ways has become characteristic of their respective fields of enquiry. Scholars from international relations, for example, hold a rationalist paradigm and believe that only states can provide the means for governance and think about governance as instating ‘regulation’ at the global level through order and stronger institutional framework and capacity. Scholars from domestic politics, on the other hand, hold a contrasting opinion and point towards the establishment of ‘softer’ and collaborative forms of policy-making that replaces more rigid centralised state controls.

A more systematic framework to access shifts in and drivers of governance is provided by Peter Hall (1993), who offers a tiered hierarchical model of policymaking that conceptualises a shift in governance. Hall’s seminal work notes the existence of ‘paradigms of politics’ and attempts to find answers to questions regarding the motivations of actions by the state, and the conceptualisation of policy process as a response to societal pressures, arguing that policies are not predetermined, but evolve gradually through changes in economic conditions and political context (Hall, 1986).

Analysing factors that drive change in policy in the context of social learning, Hall posits that the existing “policy legacies” or, “reaction to previous policies” are the principal factors that primarily affect policies and subject experts are the key agents that, while working directly with the state or in an advisory position, push the learning process forward (Hall, 1993: 276-277).

Based on various existing models of social learning at the time, Hall defined policymaking ‘as a process that involves three central variables: the overarching goals that guide policy; the techniques or policy instrument used to attain these goals; and finally the precise settings of these instruments’ (1993: 278). This definition remains relevant even to this date in identifying and mapping change in policy or, governance framework.

**Governance Paradigm Shift Framework**

Hall’s theory of social learning and paradigm change can also be used to identify the kinds of changes that have occurred in a given policy space. Based on the scientific paradigms advanced by Thomas Kuhn (1962), Hall conceptualised different orders of change: *the first and second-order*
changes are classified as the ‘normal policymaking’ or ‘incrementalism’, where simple adjustments and changes take place in policies; and a third-order change, which is marked by radical changes in all parts of policy machinery and discourse. The latter is believed to result in a disconnected process associated with periodic discontinuities in policy, which ultimately transcends into a paradigm shift (Hall, 1993).

Many scholars have since studied this theory and extended its scope and applicability by adding newer dimensions. Scholars such as Oliver and Pemberton (2004) and Kern, Kuzemko and Mitchell (2010; 2014) suggest extending Hall’s framework such that it reflected and captured the role played by institutions in driving policy change. These neo-classical scholars argue that the structure of institutions impact and effect a policy paradigm’s integration within the system and therefore provide an important insight of assessing the depth and degree of systemic change. Thus, four inter-related policy components arise: interpretive framework of ideas; goals and objectives; techniques and instruments to achieve these goals; and finally, institutions and actors.

A fifth component is also seen to exist in studies specifically focused on analysing shifts in energy systems governance. These studies suggest that energy systems (such as the electricity sector) comprise of various ‘technocratic’ sub-systems, and a paradigm shift will be incomplete, or even impossible, without a (somewhat complete) transition from ‘one set of technologies, practices, habits, regulations, values and perception to an alternative set’ (Shackley and Green, 2005).

Analysing aspects related to Socio-Technical Transition (STT) literature, as developed by researcher Frank Geels (2002), also becomes crucial as various parts of energy systems today have become highly ‘technology specific’.

Three interconnected levels were identified by Geels and his colleagues: landscape (comprising of cultural and political values and socio-economic trends); socio-technological regime; and socio-technological niches which are believed to be instrumental in directing the transition to sustainability (Shackley and Green, 2005). The STT together with the policy and governance change framework provides a more plausible and rigorous framework, incorporating various key parts of energy systems, and therefore must be included as a fifth component of the governance model for analysing energy policy paradigm shift. As per the literature, an energy system governance paradigm shift framework must take the shape as shown in Table 3.2.
Table 3.2: Paradigm Shift Framework

<table>
<thead>
<tr>
<th>Type of Change</th>
<th>First-order or second-order change</th>
<th>Paradigm shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal and objectives</td>
<td>If changes take place in only one or more levels, but not across all of them, and they are not all simultaneous.</td>
<td>Changes take place simultaneously across all levels of the framework.</td>
</tr>
<tr>
<td>Policy instruments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Policy institutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Policy paradigm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-technical transition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Shifts in Dominant Governance Paradigm: narratives of change and crisis

Change in governance or policy narrative is often seen to take place after periods of crisis, uncertainty or shock. Boin and Hart state that ‘crisis and leadership are a closely intertwined phenomenon’, and Kingdon (1984) believes that crises generate windows of opportunity that present the potential to and opportunity for reforming the existing institutional structures to implement change. Scholars like Mary Douglas argue that actors self-consciously craft solutions to the problems ‘through a process of bricolage through which they recombine already available and legitimate concepts, scripts, models, and cultural artefacts that they find around them in their institutional environment’ (1986: 67). According to this school of thought, change can result from ‘deliberate modification and recombination of old institutional elements into new and socially acceptable ways’ (Campbell, 1997:6). While relevant to other less complex policy areas, the notion of complex actor-network regimes, who often compete for greater legitimacy and control, self-organising into acceptable ways may difficult to conceptualise, but extreme significant in the present context.

Scholars from yet another school of thought combine notions of evolutionary and revolutionary concepts of change into what they call “punctuated evolution”, which according to Hay (2002) can be characterised by a ‘discontinuous conception of time’ in which periods of normal change are interrupted by more vigorous and ‘intense moments of transformation’, making the governance machinery change both in an evolutionary way i.e. incrementally over time and in a more rapid revolutionary way. However, change may not always be so neatly segregated and proceed in such an organised manner. As rightly acknowledged by Oliver and Pemberton (2014), change can be often messy, contingent, non-incremental or even revolutionary in response to crises, but might not always end up in profound change, or the adoption of a new policy paradigm.

Caroline Kuzemko (2014) provides a relevant account of change, focusing specifically on change in energy policy in the UK in late 2000. Kuzemko explains that energy policy in the UK witnessed a
phase of re-politicisation, with a higher degree of ‘formal political deliberation’, which took place ‘through the impact of narratives of national energy supply (in)security’ (pp:259). Taking unifying strands that run across both the Copenhagen School and critical security scholarship, Kuzemko writes that if the language of security is evocative and raises strong public and political interest causing governments to diverge from previous practices, paradigm change can take place in the existing practices (Kuzemko, 2014: p.260; Waver, 1995: p.54-55). Kuzemko’s theory highlights the importance of narratives and maintains that how issues are conceived and framed has the potential of pre-determining political processes, the choice and deployment of political machinery and, ultimately, the change that results.

Global Energy Governance Theory

Given the significance of energy in the modern global economy, and as problems related to security, sustainability and affordability of energy supplies take centre stage on the world’s agenda of issues that need immediate action, the inadequacies of the current governance framework in addressing various issues become all too obvious. While the theory of governance applies uniformly across most policy areas, a separate strand of literature on global energy governance has emerged as a prominent new field of enquiry in international studies over the past few years. Outlining the need for global energy governance, Florini (2008) states that energy has been governed in a piecemeal manner, in ad-hoc responses to specific problems involving specific interest groups, without due or sustained attention to externalities that it generates or over longer time horizons that it requires. These, put together, explain the thriving yet scattered research in the field, ranging across areas and covering almost all aspects related to generation, access, distribution and management of energy; and across technical, economic, socio-political and geopolitical dimensions.

Energy scholars have over the last decade been scrambling for an effective solution, or a clearer framing of problems by critically examining the application and suitability of existing theories from a wide range of disciplines against the emerging issues relevant to the global governance of energy. The importance of energy governance scholarship is further exacerbated by the inherent complexity and interconnectedness associated with the very nature of 21st century energy challenges and their systemwide ramifications and the need for a coherent framework that can address the temporal and spatial challenges associated with energy systems and their governance.

Scholars engaged in this field seek to understand and explore key elements associated with energy sector governance, such as mapping the framework, landscape and construct of actors; exploring the goals, objectives and agenda of issues that need to be governed; as well as evaluating the efficacy of existing instruments in addressing issues (Andrews-Speed & Shi, 2016; Cherp, et al., 2011; Dubash &
Florini, 2011; Goldthau, 2016). As assessment of academic work in the field helps to broaden the boundaries of perspectives and scholarly lenses through which global energy governance should be suitably and normatively analysed. Against this backdrop, a critical overview of relevant aspects of global energy governance literature is undertaken in the following sections.

The Origin of Global Energy Governance

Global Energy Governance, or GEG, as commonly referred to by scholars from the field, has been formalised as a concept only recently. Tracing the roots and origin of Global Energy Governance, de Graff and Colgan (2016) point out that the terminology or indeed the concept emerged around 2005 when it was picked up by G8 as the theme for its Gleneagles summit. Van de Graff attributes a part of the growing research in the field to two research projects: Global Policy Institute’s “Changing Rules of the Game: Global Energy Governance in the 21st Century” between 2008-2009; and the Study Group on Global Energy Governance at the Lee Kuan Yew School of Public Policy at the National University of Singapore (NUS) in October 2009 and May 2010. The former examine rules governing financial markets, trade and investment and supply risk management aspects of global oil and gas governance and the latter examine the institutions that directly and indirectly govern energy, along with other relevant details associated with these institutions.

Earlier accounts of international cooperation on energy also exist, but not under the rubric of Global Energy Governance. Van de Graff provides a summary review of some of these literary works dating as far back as the early 1980s and concludes that energy cooperation until recently failed to receive an integrated research agenda and has been largely under-theorized because of one of the following reasons: many energy experts were primarily focused with ‘how actors should respond’ to short-run market concerns and prospects, rather than on theory; lack of ‘technical understanding’ and know-how on energy related issues; or, ‘difficulties in adopting a uni-disciplinary analysis’ owing to the multifaceted nature of energy as a policy area (2015:47).

Many of these issues remain pertinent to energy governance even today, and yet Global Energy Governance research and agenda has emerged as a thriving topic not just academically but more recently on the agenda of intergovernmental and transnational organizations and is being seriously considered by countries such as the UK. A high volume of policy roundtables and consultations currently underway that call for an urgent review and reform of energy governance framework to support the shift to Net Zero economy can be attributed as a response to intensifying public protests and pressures demanding urgent tangible action to address climate change. Kuzemko’s theory (2014), narrative of crisis warrants change, perhaps provides a more plausible explanation for the growing prominence of and a renewed focus on global energy governance scholarship.
The narrative of crisis associated with the declining state of the environment globally and a desire of various state capacities to maintain secure and affordable supplies of energy in the face of the rapidly evolving geopolitical landscape of energy can be attributed to have indeed transformed the ways in which these issues are conceived. This has resulted in calls for reevaluating the global energy governance framework and agenda, which presents the potential of pre-determining political processes, the choice and deployment of political machinery and, ultimately, the change that results. This shift in focus is further corroborated by recent consultations organised by the UK Government – Reforming Energy Governance for New Zero, on a new governance regime to facilitate the shift to Net Zero (IGov, 2020). It is clear that global governance of energy possesses a high potential and is crucial to enable energy systems transition towards desired pathways.

Increasing concerns associated with climate change, an almost total transformation of the global geopolitical landscape of energy with the emergence of new producers and consumers of energy and increasing volatility of energy markets (notably oil and gas markets) have, according to Van de Graaf (2016:3), ‘created a host of externalities’ associated with global energy systems. This has led scholars to reevaluate energy from a global governance perspective and to closely investigate various aspects related to it. This shift is clearly visible in a comparative analysis of energy governance studies spanning a few decades. This comparative assessment also underscores the need for a coherent and global framework for energy governance and runs across as a common theme in several scholarly works (Dubash & Florini, 2011; Sovakool & Florini, 2009; 2011; 2012; Van de Graaf, 2013; Van de Graff & Colgan, 2016; Lessage & Van de Graff, 2016). These scholars argue that an effective transition of energy systems towards environmentally sustainable, secure and affordable pathways needs an effective global governance on a variety of energy related issues, and while select aspects are separately addressed to a certain degree by various related disciplines such as by international relations, governance and global policy literature, they remain siloed and do not adopt a unifying approach to address transnational energy policy challenges associated with technology transfer, financing, etc. The disadvantages of such a siloed scattershot approach are only too obvious as governance arrangements fall short of requirements needed to promote efficient markets or deal with externalities such as climate change or indeed provide clean and modern supplies of energy at affordable prices to millions still reeling under energy poverty.

The need for improved arrangements and framework from global energy governance are highlighted by several energy governance scholars. Florini and Sovacool (2011) state that changing governance arrangements is likely a ‘monumental governance endeavour’, but needed to ‘address numerous interrelated areas, covering issues normally dealt distinctly’ by scholars (pp. 58). A systematic analysis of past trends and factors central to shaping the global energy governance as it exists is a
necessary prerequisite for attempting any future reforms. A review of dominant energy governance paradigms and a systematic assessment of changes across various layers of energy governance framework is undertaken in the following sections.

**Changing Objectives, Scope, Paradigms and Frameworks of Global Energy Governance over the years**

**Changing Objective and Scope of Global Energy Governance**

The objectives and scope of Global Energy Governance remain central to energy governance scholarship. Under this theme, aspects related to the very construct and agenda of global energy governance are outlined. In the recent past, with energy-related developments shaping and triggering changes in the world-order and with energy assuming a central role in determining national policies and private-sector behaviour, a significant amount of work has been undertaken by energy governance scholars and socio-technical scientists analysing the existing or desired framework of energy governance globally (Cherp et al, 2011).

As rightly stated by Goldthau (2012), ‘like almost no other sector, energy reflects changing paradigm’. Scholars (notably Helm, 2007) not only trace the changes in paradigm but also study reasons that contribute to these deep shifts in energy policies or other governance arrangements. Scholars like Kingdon (1984) believe that crisis generates windows of opportunity to reform the existing structures and so change occurs.

Several new paradigms to energy governance have been studied in recent years and new narratives explored. These scholars focus on framing the agenda and setting out goals and objectives for global energy governance. These studies espouse the view that changes in various aspects of energy governance have resulted after, and as a result of, periods of crisis, uncertainty or shock. An assessment of dominant paradigms spanning four decades, and the policy agendas and energy governance patterns that came with them is provided by Goldthau, who also states that paradigm provides ‘guidance on the policy goals that need to be achieved’ and the most appropriate ‘toolbox’ for it, and are, therefore, of great importance in the scholarship of energy policy (2012). Changing paradigms have over the past decades resulted in shifts in changes in objectives, institutions and other relevant policy instruments.

**Liberal and neo-liberal framework:** According to Van de Graaf (2016) the primary role and objective of energy governance arrangements in the 1970s was linked in the face of ‘eroded capacity of traditional modes of state-based regulation to steer society’ to oversee ‘financial deregulation, trade liberalization and consolidation of global production networks’ (pp:47). This theory is also supported
by Messner and Humphrey (2006: 107), who state that early accounts of global energy governance scholarship were primarily focused on promoting a ‘neoliberal policy agenda aimed at promoting faster economic growth through internal and external liberalisation’. The Keynesian ideas that, more or less, defined not only the goals and policies but also the choice of instruments for achieving them until this period, predominantly in Europe, were replaced by deregulated, or liberalized, frameworks in the last two decades of the 20th century (Hall, 1993:79; Clift & Tomlinson, 2006:2-4). The UK emerged as the model of decentralization and marketisation in the 1980s and 1990s. Hay (2007: 82) argues that the energy policy underwent ‘technocratic depoliticisation’ whereby the responsibilities shifted from the government to the public or quasi-public authorities. According to Kuzemko (2014) the ‘narrowly defined, diminished and institutionalised’ political structures that existed were created to ‘maintain and support competition, cost efficiency and freely-trading markets’ and their inherent make-up made them stay closed to any alternative notions of energy governance (pp:15). The abrupt and radical change in paradigm from state to the neoliberal framework was also marked by newly elected politicians, notably Margaret Thatcher in the UK, Ronald Reagan in the US and Helmut Kohl in Europe, supporting a shift towards political right and economic paradigms from state to market (Goldtahu, 2012). The central idea of public choice thinkers, such as Anthony Downs, William A. Niskanen and proponents of the Chicago School of Economics, framing the state as more of a problem than a solution; and that the private ownerships-guided by profit motives-should deliver more efficiently and effectively became mainstream (ibid). While this model remained the dominant paradigm towards the end of the second millennium, studies highlight, that a shift to a new policy paradigm was already underway with the emergence of climate change, concerns over energy security and supplies, changing geopolitical landscape, and concerns over the prevalence of energy poverty.

Regulatory state framework and inadequacy of markets-concerns over climate change; energy (in)security; the rise of emerging economies: Authors like Van de Graff (2016) believe that global climate change and the need to decarbonize the economy was one of the prominent factors that spearheaded the transition away from the liberalized framework. Nicholas Stern’s words, ‘as the greatest and widest-ranging market failure ever seen’ forced policy makers and scholars to reevaluate governance structures and mechanisms (2006: i). Concerns over climate change led scholars to rethink the adequacy of the existing energy governance paradigm which predominantly included ‘market-based prescriptions, coupled with regulatory mechanisms’ (Mitchell, 2008:1). In this approach, the Government must only steer from a distance towards a set direction allowing the markets to decide the best suited means to achieve the stated objectives, with certain regulatory limitations (ibid).
Almost parallel to the emergence of concerns over climate change, there were another set of coinciding events that took place in the early 2000s that significantly altered the perceptions with regards to the security of energy supplies and brought back state intervention.

The UK, together with the USA, invaded Iraq in 2003, and scholars like Rutledge believe that ‘energy security concerns were the primary reason behind this invasion’ (Rutledge, 2007:912). As the changed narrative about energy security and security of supply -informed by the geopolitical drivers and factors- became prominent, new challenges emerged for the pro-market paradigm around mid-2000 (Kern et al., 2014). Elsewhere in the world, China and India had embarked on an aggressive economic growth trajectory, and their demand for fossil fuels had grown dramatically, causing extreme pressures on global fuel prices. But more disturbingly for traditional energy consumers, particularly the OECD countries, China, having turned a net importer of crude oil in the 1990s, started resorting to diplomatic means to secure energy for its state companies (Goldthau, 2012).

Changes in Russian energy governance had resulted in ‘restrictions on foreign investment in their energy sector’, and a number of other factors (such as the ‘appropriation of Exon-Mobil and Shell assets and the Russia-Ukraine disputes of 2006’) resulted in ‘state’s decision to take back the industry to fulfil its foreign and economic policies’ which was a clear deviation from the market-liberal direction (Locatelli, 2006:1076). A series of disputes over gas volumes and pricing between Russia and Ukraine resulted in cut-offs to Eastern-European consumers in 2006 and 2009 (Goldthau, 2012). By reincorporating state interference, Russia had invoked the factors that were understood to have caused the 1970s oil crises, and by interfering with freely delivering markets it had caused the fear of possible supply (in)security; a strong rationale for energy supply to be apportioned the status of being an issue of national security (Mitchell et al., 2001). ‘Notions of energy geopolitics, energy nationalism and energy weapons, typically embedded in zero-sum mentalities’ reflected increasing concerns over supply, investment and price risks, and all these together led to securitization and politicization of energy agenda (Goldthau, 2012: 203).

**Market failure warrants state intervention:** Two almost parallel streams of studies each approaching energy governance as a niche area emerged. Studies by energy economists and economic policy experts subscribe primarily to economic assumptions on markets, pricing and resource allocation, and address energy as an issue of market failure, and important externalities, warranting state intervention (Andrew, 2008; Ostrom, 2010; Goldthau, 2012, 2013). Another group of scholars ascribe to the perspectives of state and model energy as a subject to international geopolitical scheming; centring on the degree to which energy can be used as a foreign policy tool by energy-exporting nations; or on the consequences of a nation’s dependence on foreign sources of energy (Yergin, 2005; Youngs, 2007; O’Sullivan, 2013; Kalicki & Goldwyn, 2005 and 2013; Pascual, 2015).
Scholars ascribing to economic theories test, with varying results, the longer-term suitability of markets as a dominant mechanism for global energy governance. Markets, according to neoliberal policy experts, were the dominant and the most effective mechanism to make the supply side react to the demand increments, which, by and large, has been proven effective, as was showcased by the oil markets, effectively translating demand increases into signals for the supply side. Scholars notably, Goldthau (2012), believe that the liberal period that guided energy policy-making initiating a wave of privatisation of public utilities went in retreat with the states returning to the game. Goldthau criticizes the suitability of market-based instruments/principles for the provision of secure and affordable supplies of energy, which he classifies as a private good with the characteristics of a public good (2013:3). More details on market failure, government failure and externalities are provided by Andrew (2008), where existing approaches to solving the problems of climate change by reducing GHGE (Green House Gas Emissions) are critically analysed. Andrew argues that the problem at hand is ‘the result of a dramatic case of market failure, where organisations have failed to bear the full cost of production by passing it onto the community wherever possible’ (Andrew, 2008:393-401).

A widespread disagreement among scholars on the appropriateness of markets as the only suitable instrument to regulate energy exists. Some like Youngs, with specific reference to EU, point out that energy policy ‘hovers ineffectively between market and geopolitics’, and that the ‘market-governance’ discourse needs to combine markets and politics more closely for energy policy to be better integrated across all policy areas (2007:1-16). The uniqueness of energy is distinct from the rest of the economy on account of its capital-intensive, monopolistic and rent-seeking nature (a concept in public choice theory, as well as in economics, that involves seeking to increase one’s share of existing wealth without creating new wealth), along with the role that states must play, is highlighted in the works by Bressand (2013) and Andrew (2008). These authors maintain that a robust analysis of the prevalent global energy paradigm should be an interplay between markets and states; between resource nationalist or market-friendly ones; but capture the manner in which states and an array of actors interact through the energy value chains and energy resources; which is best done through a political economy perspective (Bressand, 2013).

**Changing energy geopolitics warrants state intervention:** The frameworks that establish an understanding of exchanges between energy geopolitics and markets, and the underlying narratives of global peace and world security have been explored at length by foreign policy and international relations scholars. A large volume of work exists in the area, and many scholars use different entry points to approach energy governance. Many espouse the view that the rising demand and shifting geography of supply are the primary reasons to re-evaluate energy governance, while others analyse
energy governance in the context of emerging changes in resource dynamics, actors and institutions, but primarily in the specific context of countries.

Authors such as Kalicki & Goldwyn (2005) identify energy and security as crucial considerations to the foreign policy agenda of every industrial and industrialising nation and call for an integration of energy policy with the foreign policy, in such a way that while the new policy paradigm addresses the impact of its demand on the exporting countries, it also builds stronger security systems that can better withstand risks of disruption. According to these authors, the bilateral and multilateral relationships, security alliances and free-market trading systems serve to promote the security of energy supplies. The lack of proper long-term planning, or as they describe it: a ‘policy-myopia’, not just increases the risk of internal instabilities, but causes longer-term problems associated with climate change and escalating remediation costs (2005:545-577).

Other notable groups of authors (not just, but notably, Westphal (2006), Pascual (2015), Pascual and Zambetakis (2010), O’Sullivan (2013)), evaluate the energy-security nexus and approach governance from a reductionist standpoint, ascribing to country-specific context to energy governance.

Westphal (2006) states, referring to energy governance in the EU, that attempts to govern and respond to energy challenges have faced serious limitations as energy policy is widely dominated by geopolitics. Energy governance, he writes, is “exercised [in the EU] in a ‘tension between power-based geopolitics and multilateral cooperative governance” and the implicit structures of governance have been in a constant state of “flux, driven by [an ongoing] struggle over capturing of rent and over prices” (44-47).

While Westphal’s analysis of energy governance challenges focuses on the European context, Pascual (2015) and Megan O’Sullivan (2013) evaluate evolving relationships between energy and geopolitics in the United States. According to Pascual, new resources (such as shale gas) create new geopolitical tools and opportunities and provide countries with new leverage to advance their agenda globally. He posits that in a rapidly changing energy market and foreign policy environment, any approach to governing energy must be based on an understanding of how these interact and a clear identification of their points of intersection. This must integrate an understanding of the shifts in demand and supplies together with any likely risks of disruption. Pascual also exerts the importance of understanding how various market forces work and how they impact energy security, incentives for investment, broader implications for climate change and an overall impact on energy
access (2015:3). A ‘rule of six’ is proposed to help understand if an intervention in energy markets by energy producers like the United States, to meet their geopolitical pursuits ambitions is likely to prove effective (2006:29).

O’Sullivan traces the recent changes in America’s resource dynamics resulting from the technological breakthrough of hydraulic fracturing and horizontal drilling and she links this to the country’s military positioning, stating that energy security no longer relates just to the security of supply, but demand security also plays an equally vital role, particularly for countries reliant on revenues from energy exports. She posits that the security of infrastructure and transit routes are key pre-requisites to ensure that energy remains accessible and affordable; and energy security additionally implies ‘having access to affordable energy without having to contort one’s political, security, diplomatic, or military arrangements unduly’ (2013:30-31). A framework is presented by O’Sullivan for exploring the interaction between energy and security including how it relates to hard security (through a ‘grand strategy lens’ that reveals the interactions between ‘countries, actors and global institutions’). O’Sullivan further explores the role of energy as a ‘weapon’; as a means (or ends) to the grand strategy; for pursuing energy-related or independent goals for shaping their specific or broader national interest or for providing the revenue for pursuing various vested agendas (O’Sullivan, 2013:29-43). Others like Yergin (2005) recognise the need to reevaluate energy security in the light of new and emerging paradigms, proposing as a guide for countries a new framework that includes: ‘maintaining a diversification of supply; a security margin in the energy supply system; recognising the need to integrate with the overall market; maintaining an exchange of information across channels; and, by expanding the concept of energy security and making it more overarching, inclusive and enabling and the protection of entire supply chain’ (Yergin, 2005: 51-64).

The political aspects of energy supply and demand in situations of crisis are evaluated by Pascual and Zambetakis (2010). Much of their analyses focus on disruptions arising out of energy dependence on politically unstable producers (reliance on the Middle East for oil, Russia for gas, Venezuela, Iran to name a few), which ‘depend on large export revenues to maintain stability’ of domestic and foreign policies (2010:10). Pascual and Zambetakis highlight that a growing acceptance of global climate change and the associated political narratives and debates are opening new fronts in the geopolitics of energy. They also address the ‘fragility of international fuel markets and the nexus between

---

3 The Rules propose that any given intervention must be assessed against six market and institutional factors that will influence the desired outcome. The six market interventions are tactical options that can influence energy markets to serve national security interests. The first five tactics reflect the history of energy trade over the past century. The last tactic reflects the emergence of climate change as a foreign policy issue and the imperative to understand whether national and global climate policies will influence investment choices to increase the competitiveness of clean and renewable energy and energy efficiency (Pascual, 2015:11).
energy security, climate change and nuclear energy and proliferation’ (2010:11). They assert that an understanding of these interactions is required for effective governance of energy (Pascual and Zambetakis, 2010:9-25).

A different group of scholars focus largely on the geopolitics of specific resources and thus address energy governance as governance of these resources. These scholars focus on the pressure points created by these energy resources and analyse how an effective governance can intervene to create channels that disperse and alleviate such tensions. Boscheck (2007) analyses the role of national oil companies (NOCs) and highlights their importance in aligning political and market interests and providing an institutional response to international oil companies (IOCs). Details on the roles and responsibilities of NOCs can also be found in McPherson (2003), while Ledesma (2009) analyses the relationship between the two.

The Paradigm of Interventionism: This illustratively detailed account of scholarly work clearly indicates the dominance of the energy security narrative in the energy policy agenda. The framework of ideas that guided energy policies in this period circled the changed notion of energy merely being a ‘tradable-commodity’ to the lifeblood of a modern economy (Kuzemko, 2014: 267). The emergence of climate change, energy poverty, changing energy landscape and other externalities led to highly politicised and public debate, and signalled a further shift in the prevailing energy governance narrative at the time and paved the way for, what Helms (2007:12) calls, ‘structural shifts’ in markets, as well as more ideational shifts, according to Goldthau (2012: 204). Energy no longer was just of strategic importance to countries but was now at the core of global climate change, while simultaneously crucial for national development. There was, thus, a clear shift in the objective of energy governance, and markets were no longer the ‘uncontested means’ for achieving these objectives, as, in Goldthau’s words, ‘...[markets] could fail in delivering a reliable supply of energy at affordable prices; they could fall short in providing universal access to modern forms of energy; and they might not be able properly to price in key externalities such as GHG emissions’ (2012:204).

Goldthau (2012) describes the new paradigm as one of ‘interventionism’, whereby energy primarily remained subject to private provision, with the re-emergence of some sort of measured state intervention to fix perceived shortcomings of market-based methods. However, with a more calculated resistance to avoid any shift away from pro-market governance, very few changes were observed across all other levels of the framework. Despite the definitive re-politicisation of the energy policy paradigm and the re-prioritisation of energy governance objectives, not much deviation otherwise can be seen in the mechanisms and institutions responsible for energy
governance. With the existing policy and governance framework remaining mostly intact, the paradigm of interventionism as advanced by Goldthau does not fulfil the criterion outlined by the energy system governance paradigm shift framework and cannot thus be called a new paradigm but a modified version of the previous paradigm. Findings from a high-level assessment across the 5-levels of paradigm change framework as applied to Global Energy Governance are presented in Table 3.3.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The framework of Ideas or, Interpretive framework</strong></td>
<td>Energy was a non-storable commodity; Fundamentalist view that competitive markets as the most-suited mechanism for achieving energy policy; Suggestions emerged to take a new approach to energy-related problems.; Pledge to reduce CO₂ emissions by 20% from the 1990 levels by 2010; States emerged as rule setter and regulator.</td>
<td>Energy continued to be understood as the natural function of competitive markets;</td>
<td>Emergence, of ‘climate-security-energy nexus’, energy was no longer a non-storable/non-tradable commodity but the most integral element, crucial for the socio-economic prosperity of the nation. It was now regarded as the key national asset. State as a stakeholder of ‘public interest’</td>
<td>Growing concerns over increasing emissions; Concerns over balancing energy policy objectives; Energy had established its significance as being vital to the country’s socio-economic growth; Restricting global temperature rises to 1.5 degrees C by 2050.</td>
</tr>
<tr>
<td><strong>Goals and objectives of Policy</strong></td>
<td>Maintaining affordability and security of supply and reducing the emissions through competitive markets.</td>
<td>Energy jumped up on the hierarchy of policy objectives; The geopolitically informed narrative of crisis resulted in ‘re-politicisation’ of energy policymaking</td>
<td>Climate change and energy security</td>
<td>Main objectives: security of supply and demand; international security; economic development alleviating energy poverty; domestic good governance; environmental sustainability</td>
</tr>
<tr>
<td><strong>Policy/Governance Institutions</strong></td>
<td>Regulatory authorities were created; more regional institutions emerged to create awareness on relevant issues; but limited structural changes; landscape of actors-fragmented</td>
<td>Public provision</td>
<td>‘Pigovian’ cum Colbertist approach (Goldthau, 2012:204)</td>
<td></td>
</tr>
<tr>
<td><strong>Policy Instruments/agenda</strong></td>
<td>A regulatory framework developed in countries like the UK. Here, direct top-down intervention by the government was replaced by the exchange between the utilities and the regulator; Policy instruments were mostly structured around market-based mechanisms and delivery</td>
<td>In response to the concerns over the security and further to re-politicisation of energy, focus shifted to bringing about self-sufficiency in energy supply and demand; plans to build new nuclear reactors in the UK to meet the growing demands of energy and bringing down emissions.</td>
<td>More technology-specific policymaking ensued to be able to deliver the climate-renewable objectives; a renewed focus resulted in technological innovation.</td>
<td>Paris COP 21 Agreement was signed in 2015 and adopted as a coherent narrative that determined national policies and efforts against climate change; Nuclear New Build plans approved in the UK; Renewable technologies modified the energy mix in many countries; a low-carbon transition plan to include nuclear, renewable and clean fossil fuels through Carbon Capture and Storage</td>
</tr>
<tr>
<td><strong>Socio-technical transition (STT)</strong></td>
<td>Policy-making proceeded mostly in a technology-neutral fashion, with some gaps opening; the role of renewable was highlighted, while nuclear and coal was banded as unattractive, and gas was highlighted as a transition option;</td>
<td>In response to the concerns over the security and further to re-politicisation of energy, focus shifted to bringing about self-sufficiency in energy supply and demand; plans to build new nuclear reactors in the UK to meet the growing demands of energy and bringing down emissions.</td>
<td>More technology-specific policymaking ensued to be able to deliver the climate-renewable objectives; a renewed focus resulted in technological innovation.</td>
<td>Nuclear New Build plans approved in the UK; Renewable technologies modified the energy mix in many countries; a low-carbon transition plan to include nuclear, renewable and clean fossil fuels through Carbon Capture and Storage</td>
</tr>
<tr>
<td><strong>Policy paradigm</strong></td>
<td>Pro-market paradigm/ Liberalism</td>
<td>Re-politicised policy paradigm, resulting in a flurry of policy documents, announcements and consultations</td>
<td>Interventionism: More active interventionist approach by the government.</td>
<td>Fragmentation: Inter-paradigm borrowing; rejection of neo-liberal and market-based ideology did not take place; however,</td>
</tr>
<tr>
<td>Paradigmatic Shift?</td>
<td>There remained a high degree of inertia and path-dependency in global energy governance. Though the emerging debate did make the governments to re-think the policy, not much changed in the technology preferences or, in the mix of policy instruments.</td>
<td>Though there was a very visible re-politicisation of the global energy governance paradigm, with the government actively intervening and setting directions and re-prioritising energy objectives. However, the onus to deliver these policies remained with the market forces.</td>
<td>In the wake of intensive re-politicisation of the paradigm, and under mounting evidence of policy failures, radical changes could be observed in the governance structures underscoring energy governance.</td>
<td>interventionist policymaking had set in; state-market hybrids</td>
</tr>
</tbody>
</table>
Need for Coherent Framing of Objectives and Scope for Governance of 21st Century Energy Systems

As alluded to by many scholars above, energy governance objectives have been the guiding reason motivating the efforts to find a suitable paradigm or framework by scholars over the years. As rightly argued by Van de Graff and Colgan (2016), the global energy governance framework has evolved beyond the narrow dimensions of energy security or the need for collaborative governance alone to include multiple goals of security of energy supply and demand, economic development, international security, environmental sustainability, domestic good governance to address the challenges associated with leading the transition of contemporary energy systems. Lack of clarity on objectives of Global Energy Governance is believed by scholars like Dubash and Florini (2011) to ‘impede coordination and communication’.

A growing number of international relations and global governance scholars have recently been focused on a coherent framing of aspects related to Global Energy Governance (Florini, 2008; Florini & Sovacool, 2009; Colgan, 2010; Lessage et al. 2010; Dubash & Florini, 2011; de Graaf & Colgan, 2016). These scholars argue that it is often difficult to conceptualise energy governance as a coherent field because of the multiple levels of fragmentation across various layers of the energy supply chain, but highlight that clarity on what in energy systems needs to be governed is paramount. Some scholars (like Cherp, Jewel and Goldthau (2011); Florini and Sovacool (2011); and Dubash & Florini (2011)) systematically study and identify the range of objectives or issues that require global energy governance and outline the global energy governance landscape.

Dubash and Florini (2011) group various energy governance objectives under four headings, namely: energy supply security and geopolitics; energy poverty; environmental externalities; and domestic governance. In a review of the research agenda associated with Global Energy Governance, Van de Graaf & Colgan (2016) provide a more comprehensive list of five objectives and outlines ways for achieving these objectives. This study also provides a distinction between the potential scope and actual scope of Global Energy Governance. Any social, political or economic issue that can potentially transcend borders and is connected with any part of the energy supply chain is classified as the potential scope of Global Energy Governance; active scope, on the other hand, includes issues that receive active attention by a set of relevant actors (de Graaf & Colgan; 2016:3). This listing includes security of supply and demand; economic development; international security; environmental sustainability; and domestic good governance, as listed in Table 3.4.
In analysing the literature on global energy governance objectives, two important issues emerge, and they are: there is a growing recognition that mechanisms and frameworks related to global governance for energy are poised to play an important role in guiding the desired transition of energy systems in the future; and that several key issues and areas need stronger representation and better integration into the global framework, if one is to address the challenges facing energy systems in the 21st century. One such area is energy justice, which is grossly underrepresented in the literature and exists somewhat in isolation.

Energy justice is an important component in ensuring an equitable, sustainable, and fair governance of energy globally. It serves as the connecting thread that in many ways brings together all the fragmented pieces in the global governance of energy. According to Jenkins et al. (2016), energy justice is a cross-cutting concept that seeks to apply justice principles to energy policy (c.f. McCauley et al. 2013), energy production and systems (c.f. Heffron and McCauley, 2014), energy consumption (c.f. Hall, 2013; c.f. Jenkins et al., 2013), energy security (Sovacool et al., 2013), the energy trilemma (Heffron et al., 2015), the political economy of energy (Jenkins et al. 2016) and climate change (Sovacool, 2013; Sovacool and Dworkin, 2014). While many scholars have highlighted the need for human-centred research methods and ethics in energy studies, Sovacool’s (2014) work on the issue is noteworthy. According to him, “energy justice... recognises that energy needs to be included within the list of things we prize; how we distribute the benefits and burdens of energy systems is pre-eminently a concern for any society that aspires to be fair’ (Sovacool, 2014:15). The research on energy justice seeks to answers questions relating to the fairness or distribution of costs and benefits of production and consumption of energy; about the fairness of leaving behind legacy issues like nuclear waste disposal, climate change, resource depletion etc. for future generations (ibid). A comprehensive account of philosophical approaches to energy justice can be found in the work by Sovacool and Dworkin (2014).

The large body of literature reviewed above outlines the principles critical to defining and understanding the broader paradigms that have historically framed energy policy and its governance. It sets the scope and highlights the objectives for a Global Energy Governance paradigm. Another key strand in the global energy governance literature is concerned with mapping
the architecture and landscape of the global energy governance paradigm. This is particularly relevant as the demarcation between components of national sovereignty or national energy governance and regional or Global Energy Governance is an important one. Further insight is also to be gained from a review of actors and institutions responsible for governing energy on their deemed capability in dealing with potential issues that are likely to seriously challenge the objectives of Global Energy Governance.

Global Energy Governance Architecture

Biermann et al. (2009) define “global governance architecture” as “the overarching system of public and private institutions that are valid or active in a given issue area of world politics”. A number of studies evaluate the make-up, role and adequacy of the current framework in addressing the contemporary energy policy challenges. These studies present a comprehensive review of global energy architecture and attempt to address the question of “who governs energy”.

In mapping the global energy governance architecture, de Graff and Colgan (2016), provide a review of previous efforts by Suding and Lempp (2007), Kerebel and Kepller (2009), Sovacool and Florini (2012), Colgan et al. (2012), Leal-Arcar and Filis (2013), Wilson (2015) and Escribano (2015) (pp:5). A large number of global energy governors have been identified by scholars. A wide range of institutions and bodies are included within this category, ranging from intergovernmental organisations and summit processes to international NGOs, multilateral institutions and transnational networks of ‘advocacy to quasi-regulatory private bodies’, networks and partnerships (Sovacool and Florini; 2012). An illustrative map of the current global energy governance architecture based on the literature review is presented in Table 3.5.

A number of studies also provide a detailed account of select international organizations such as the IEA, OPEC, REEEP, ADB. Some scholars, notably Griffin (1985) and Goldthau and Witte (2011), analyse OPEC’s role since it was created in 1960, in regulating the global oil market and its effectiveness going forward. Florini’s (2011) exhaustive account of IEA, traces its origins in response to oil-price shocks of the early 1970s and highlights the challenges it faces in the 21st century. Details on another group of international institutions (REEEP, IEA, G8 and ADB) are presented while analyzing the gaps and prospects for effective governance. Karlsson-Vinkhuyzen and McGee discuss the relationship between legitimacy and power in global governance, outline a framework for evaluating the normative legitimacy of such governance fora and present a detailed description of various ministerial fora (Asia-Pacific Partnership on Clean Development and Climate (APP), G8, Major Economies Meetings (MEM)) comparing them against United Nations Framework Convention on Climate Change (UNFCCC) and highlight pervasive fragmentation in energy governance (2013:56-78).
Details of other governing bodies in energy like Association of Southeast Asian Nations (ASEAN), REEEP, ASEAN Regional Knowledge Networks (for example, on Forests and Climate Change (FCC) and Forest Law Enforcement and Governance (FLEG)) are available in studies by Poocharoen and Sovacool (2012). These studies highlight that currently the governance landscape is dominated by intergovernmental institutions or UN bodies, more notably, the UN Framework Convention on Climate Change and its Paris Agreement (UNFCCC/PA), the International Energy Agency (IEA), the World Trade Organization (WTO), the Group of 20 (G20) and the World Bank, who can set rules, provide financing and investment, share knowledge and learning.

The review of the literature points out that while global energy governance framework has more recently evolved beyond the narrow dimensions of energy security or the need for collaborative governance alone to include multiple goals of security of energy supply and demand, economic development, international security, environmental sustainability, domestic good governance; the framework is scattered, chaotic and fractured. The review also highlights that there are significant gaps in the efficacy of the actor-network-institution mesh in dealing with issues both within the actual as well as potential scope of Global Energy Governance. The mandate of actors and bodies responsible for addressing issues related to energy equity and access is severely limited and found to exist only in the periphery in certain partnerships and processes. Furthermore, there is hardly any relevant global representation of India or south-east Asian countries or other emerging economies, and almost no forum to discuss coal is found to exist.
### Table 3.5: Mapping the Global Energy Architecture

<table>
<thead>
<tr>
<th>Key international organizations</th>
<th>Key summits and agreements</th>
<th>Partnerships and programmes</th>
<th>International not-for-profit organisations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key United Nation bodies and processes; OPEC; IEA; World Energy Council (WEC); Global Environment Facility (GEF); World Council for Renewable Energy (WCORE); International Renewable Energy Agency (IRENA); World Council for Renewable Energy (WCRE); Association of Southeast Asian Nations (ASEAN); European Union (EU); International Atomic Energy Agency (IAEA); Organization of the Black Sea Economic Cooperation (BSEC); Shanghai Cooperation Organization (SCO); Southern African Development Community (SADC); South Asian Association for Regional Cooperation (SAARC); Renewable Energy and Energy Efficiency Partnership (REEEP); European Renewable Energy Council (EREC); Global Village Energy Project (GVEP); Asian Development Bank (ADB); World Bank Group, European Bank for Reconstruction and Development (EBRD); African Development Bank (AfDB); Inter-American Development Bank (IDB); International Fund for Agricultural Development (IFAD); Small-Scale Sustainable Infrastructure Development Fund (S3IDF); World Business Council on Sustainable Development (WBCSD);</td>
<td>G8; G20; Conference of Parties (COP); Jeddah Energy Summit; International Energy Forum; Summit of the Americas; Asia-Pacific Economic Cooperation (APEC); Energy Charter Treaty (ECT); Energy Community Treaty; International Partnership for Energy Efficiency Cooperation (IPEEC);</td>
<td>Asia-Pacific Partnership on Clean Development and Climate (APP); Global Bioenergy Partnership (GBEP); Johannesburg Renewable Energy Coalition (JREC); Mediterranean Renewable Energy Programme (MEDREP); IEA’s Networks of Expertise in Energy Technology (NEET); Partnership for Clean Indoor Air (PCIA); Global Network on Energy for Sustainable Development (GNESD); International Science Panel on Renewable Energies (ISPRES); Society for Solar Energy (ISES); Global Energy Network Institute (GENI); Central Asia Regional Economic Cooperation (CAREC); World Sustainable Development Forum (WSDF); International Network on Gender and Sustainable Energy (ENERGIA); Green Climate Fund (GCF); Global Alliance for Clean Cookstoves (GACC); Acumen Fund (AF); Solar Electric Light Fund (SELF); Global Energy Efficiency and Renewable Energy Fund (GEEREF); Clinton Climate Initiative (CCI); Partnership for Clean Fuels and Vehicles (PCFV); Efficient Energy for Sustainable Development Partnership (EESD);</td>
<td>Energy Through Enterprise (E+Co); International Institute for Energy Conservation (IIIEC); International Network for Sustainable Energy (INFORSE); Appropriate Infrastructure Development Group (AIDG); Collaborative Labelling and Appliance Standards Programme (CLASP)</td>
</tr>
<tr>
<td>Energy Security; Economic Development; International Security; Environmental sustainability; domestic good governance; Transnational governance;</td>
<td>Transnational governance; Domestic-international interaction</td>
<td>Transnational governance; Domestic-international interactions</td>
<td>Participation in intergovernmental processes</td>
</tr>
<tr>
<td>Includes: UN Commission on Sustainable Development (UN-CSD), United Nations Department on Economic and Social Affairs (UN-DESA), United Nations Environment Programme (UNEP), UNFCCC (United Nations Framework Convention on Climate Change)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

General note: Limited by objective; limited regional mandate and reach; Limited regional scope; Limited by energy resource; regional reach and legitimacy; Limited legitimacy.
Gaps in the Global Energy Governance Framework

The need for a common governance framework, or rule systems, that reflects shared principles, better capacities and coherence is a necessary way forward and essential for plugging the gaps that currently exist in energy governance. A notably growing number of studies exploring energy governance frameworks transcending beyond just the national level highlight (or allude to) the need for a more central body, or process, with greater reach and legitimacy than any institution that exists at present. Many scholars like Dubash and Florini (2011) (also Cherp et al., 2012; Florini, 2008; Goldthau & Witte; 2009) highlight the need for a broader framework to understand energy governance beyond the national level. This new entity could play a more effective role in governing energy globally (Goldthau and Witte, 2009, 2010; Florini, 2008).

Other scholars, like Florini (2011) maintain that IEA, notwithstanding its limited membership, acts as a global focal point undertaking the role of an overarching intergovernmental organisation on key energy governance issues. But such a claim can be contested; even if IEA does already play such a role, which can be challenged on several grounds, including its membership, its efforts need to be consolidated simply on grounds that it has little, if any, mandate for influencing policy decisions by non-member countries. This includes, but is not limited to, decisions on resource use, laws and directions on climate change and funding allocation to support and promote clean technologies. Perhaps there may be a need for IEA’s membership charter to be revised and extended to include all the countries of the world. But the difficulty (and predicted impossibility) of such a suggestion is an obvious one. Some scholars even highlight the need to adopt an entirely new structural regime or adapt the structure of the existing framework of global energy governance such that all the pressing challenges facing energy policy are included in the agenda for collaboration and resolution by all the relevant stakeholders from across the world – a herculean effort in every manner (Hirst & Froggatt, 2012).

This section has attempted to provide an account of global governors currently influencing energy policies and practices globally. This account is by no means complete as such an account will be beyond the scope of the current work. The objective to review the landscape and architecture of global governors of energy was to review the variety of mechanisms available to address the daunting issues that fall within the potential scope of issues requiring global energy governance. A number of issues became evident, including the following as also identified by Florin & Sovacool (2009:5246):

- Failure of existing institutions to develop necessary rules and channel the necessary resources to meet these challenges, due to limited scope, membership, mandate, etc.
• Fragmentation of cross-border energy governance, to the degree it occurs, by energy source or sector.

• The near impossibility that any inter-governmental organization or regime will bring all the major players together to harmonize all their resources and energy policies.

• That energy agenda globally will be governed by an array of different types of actors, with widely ranging claims to legitimate authority, attempting to set rules on different parts of energy montage.

• The continued prevalence of the ‘paradox of sovereignty’: aspects related to energy security will continue to be ‘crucial components of national sovereignty’ and national governments will continue to reign above Global Energy Governance (de Graaf and Colgan, 2016: 4). International cooperation will be valued, but only in so far as it does not slow down or interfere with the set domestic policies (McGowan, 2009:21).

The question remains: How can transnational issues related to global energy systems be governed ‘effectively’, in recognition of the factors summarized above, and lead them towards the desired goals? Multiple perspectives prevail. There seems to be growing consensus that both the top-down steering by centralised government structures as well as the liberal free-market approach have been (and will be) ineffective on their own in dealing with the challenges of energy system transitions and global energy governance (Loorbach, 2010). It is also practically impossible to imagine any degree of success in implementing policies without them; innovative and flexible modes of governance that balance the energy system transition will be needed to facilitate the generation and implementation of innovative ideas and alternative agenda needed for successful implementation of energy policies globally. Scholars like Cherp, Jewell and Goldthau (2011) have used complexity theory, while others such as Raustiala and Victor (2004) prescribe a ‘regime complex framework’ to address these challenges.

**Regime Complex Framework for Reflexive Governance:** Some scholars call for “reflexive governance” (Voss & Kemp, 2005) for energy systems (or, other large technical systems) which are intertwined with multi-actor, multi-network “regime-complexes” (Raustiala & Victor, 2004), where transformation can be seen to be limited by the ‘limits of conventional steering approaches’ to achieve the desired policy objectives (Voss & Kemp, 2005, p. 18). Scholars like Colgan et al. (2012) argue that ‘no single account can match-up and cover the range covered by the full energy regime complex’. This group of scholars theorise the mix of institutions and actors as a single entity or a “regime complex” and access its dynamic behaviour. Raustiala and Victor (2004) define ‘regime complex’ as an ‘array of partially overlapping and non-hierarchical institutions governing a particular issue area’.
Analysing the regime complex for climate change, Keohane and Victor (2011), argue that while an integrated regime governing effort to limit the extent of climate change and achieving decarbonisation objectives does not currently exist, a loose mesh of sometimes conflicting, often mutually reinforcing, ‘narrowly-focused regulatory’ nested regimes or regime-complexes can be found to exist. These regime-complexes are created by the diversity of structures and interests that are inherent in the political, social and geopolitical landscape of energy.

**Polycentric Governance:** Scholars like Cherp, Jewell and Goldthau (2011); (also Ostrom, 1980; Carlisle, 2019) ascribe to polycentric governance systems, given their ‘enhanced adaptive capacity, provision of good institutional fit for natural resource systems, and mitigation of risk on account of redundant governance actors and institutions’. Studies that are based on the complexity theory also argue that given the need to address multiple interconnected challenges associated with global energy systems, a reductionist approach whereby the role of governance institutions and mechanisms analysed in isolation with one another, must be replaced with a polycentric governance system which can effectively deal with the interconnected energy challenges.

Andrews-Speed & Shi (2016) posit that polycentric governance applies particularly well to the provision of global public and common goods which requires governance regimes to ‘simultaneously encourage participation, provide coordination, draw on or deliver reliable information, promote thoughtful deliberation and decisions, and instate equitable and legitimate incentives for compliance’ (pp:200). Sovacool (2011) believes that polycentric approaches to global energy governance, when done right, can offer ‘equitable, inclusive, informative, accountable, protective and adaptable framework for promoting renewable energy and energy efficiency, fighting energy poverty, reducing greenhouse emissions, and improving energy security’ (2012:3842). Other studies (by Hooghe & Marks, 2003; Ostrom 2010) also argue that these are better suited to delivering complex global public goods.

Complex systems scholars suggest that polycentric governance works well even for complex energy systems-which needs ‘vertical and horizontal coordination between actors, exchange of knowledge and information, engagement with a wide range of actors and reconciliation of multiple priorities, interests and values’ (Andrews-Speed & Shi; 2016:200).

More recently, transition Management scholars, notably Derek Loorbach (2007; 2010), outline the tenets of governance of complex systems incorporating insights from governance literature and complex systems transition. Based on the thinking outlined above and observations from policy experiences from complex systems, Loorbach’s transition management framework consists of interconnected spheres (each representing a specific aspect or type of governance activity) that
offer an outlook of how steering and governance processes can be actively influenced (2010). This framework consists of elements of polycentric as well as reflexive governance.

Summary: A vast volume of literature relevant to various governance theories has been presented in this section. All these together establish a familiarity of how change typically occurs across energy governance paradigms. An overview of relevant concepts, such as objectives, frameworks, and architecture of global energy governance is presented. The theories outlined in this section showcase that the prominent narrative of crises in the past had resulted in significant changes in global energy governance paradigms. These changes have so far only neem first or second order, while on others, but depending on the narrative, total paradigmatic shifts in all layers of global energy governance framework can occur. To what degree the governance framework changes is less important to how this change impacts the effectiveness of actors and governors in delivering the objectives.

Studies show that a new global governance paradigm is currently in the making with growing prominence of and rising concerns about climate change. Decarbonisation objectives are leading public debate at all the relevant energy platforms. The multipolar nature of global energy systems, and, the fragmented global energy governance landscape comprising of narrow constructs or interests of a specific group of actors or pool of resources severely restrict their capability to address long-term challenges that are likely to emerge over the next several decades. But for an effective reform in the processes and arrangements, there needs to be a better insight into what are the long-term scenarios that these reformed structures need to or are likely to address. The following sections of the thesis undertake a system dynamics model-based analysis into the likely scenarios that may emerge from varying oil price signals and the continued consumption of coal for power generation in India.
Chapter 4. A System Dynamics Based Analysis into Global Oil Exchanges and Emerging Dynamics

Context

Oil continues to remain strategically important to our energy systems, given its role in influencing energy markets, economic shifts, and global geopolitics. Despite a strong policy rhetoric supporting a transition to net zero emissions, the increased importance of petrochemicals together with a projected demand growth in developing countries is likely to drive a growth in oil consumption by almost 30% by 2040 (IEA, 2018). Amidst increasing geopolitical tensions in the Middle-East and continued price volatilities, uncertainties in demand and supply are predicted to intensify as countries try to rebalance their economic, environmental and energy priorities. These uncertainties, influencing several key aspects associated with the location of oil reserves, transit routes, trading mechanisms, demand centres and prices, present significant challenges to the ongoing debate on energy transition. A clear, coherent and evidence-based policy framework that examines the long-term dynamics of resources and the prevailing context of market and policy paradigm is critical for successfully planning the future energy paradigms.

This chapter presents a System Dynamics (SD) model covering a period of 50 years from 2015 which captures the feedbacks that influence endogenous oil price formation and its impact on observed real-world oil trends. The SD-based analysis accommodates delays, constraints and information gaps and facilitates a rational representation of physical stocks and flows as well as nonlinear causal linkages that drive decision-making in the global oil system. The use of SD provides insights (intuitive and counter-intuitive) into the macro-level dynamics of global oil exchanges and permits assessment of the potential impact of future changes in system behaviour and seeks to answer the research sub-question: What will the future effect of oil price points be on the demand of oil? The impact of interactions between oil price, aggregate supply and demand are critically evaluated by the SD model using a series of scenarios.

Overview

Ever since its first discovery in Pennsylvania in 1859 and the discovery of a large petroleum reserve in Texas in the early 20th century, oil has reinforced its role and retained its significance, as a global commodity and a strategic fuel. The past century has witnessed systemic changes in the world economy and political order. The rules of the game are rapidly changing with the rise of new demand centres-mainly China (and to a lesser extent India), expansion in unconventional oil
production and mounting concerns over a rapidly changing world climate. These factors combine to affect the security of supply and economics of oil. Despite this, oil still remains at the centre of foreign and energy policy narratives across the world in the twenty-first century, much as it did throughout a good part of the twentieth century. The Twentieth Century saw key events, such as the Suez Crisis in 1956, the 1973 Arab oil embargo, the Iran-Iraq war in 1980, and the 1990 and 2003 Gulf wars. The Twentieth Century also saw the formation of Organisation of the Petroleum Exporting Countries (OPEC) and in response, the International Energy Agency (IEA). For approximately 100 years oil has impacted and determined the very principles and fundamentals of energy governance (Betts, et al., 2006.). Despite the urgent need to decarbonise, and the goal of an end to the age of oil being increasingly plausible, simple realism requires one to acknowledge that oil remains central to any contemporary considerations of energy policy and energy governance. For example, in 2019, oil contributed towards 33.1% of total energy consumed and oil demand growth and despite the manifest threat posed by climate change oil demand was in 2017 forecast to remain strong reaching 105 Mb/d (million barrels per day) by 2040 (International Energy Agency, 2017). The IEA prediction from 2017 is broadly consistent with a more recent assessment from BP of 100 Mb/d, presented in Figure 1 (Looney, 2020)).

![Primary Energy Consumption 2019](Figure_4.1_Oil_Shares.png)

**Figure 4.1: Oil's Share in global primary energy mix in 2019**

*SOURCE: (Looney, 2020)*

Oil price shocks have historically been linked to macroeconomic performances of various economies (Barsky & Kilian, 2004); (Hamilton, 2003); (Allsopp & Fattouh, 2016)) and have been known to impact seriously on policy choices. Oil price movements since the 1970s have triggered many changes in the world order and led to economic recession, inflation, and sometimes to a
concentration of wealth in OPEC nations, but more typically to volatile cycles of boom and bust across the oil industry (Morecroft & van der Heijden, 1992). It is sometimes said that oil is the only genuine market commodity in energy. Coal, natural gas and electricity lack transparent liquid markets and are overly shaped by location and network effects. As an energy-dense and easily-transported fluid, oil is as good as it gets in energy markets. As the world seeks to decarbonise and to eliminate most uses of petroleum what will happen to energy markets? Some might celebrate the elimination of supply and demand volatility and the direct consequences of price spikes and crashes, but these things are a sign of market price formation and they represent market signals for investment. The oil industry has been built around such realities and the industry works well despite, arguably indeed, because of, the price volatility. Things, however, can go too far and it was in direct response to oil price shocks that the first major structural changes to global energy governance were instituted through the formation of IEA and the setting-up of oil-surplus quotas, etc. (Samii & Teekasap, 2010). Figure 2 charts the historical trajectory of the oil price.

![Figure 4.2: Crude Oil Prices 1861-2016 Source: (Dudley, 2017)](image)

*Note: 1861-1944 US Average; 1945-1983 Arabian Light posted at Ras Tanura; 1984-2016 Brent dated.*

The very wide time frame of figure 2 shows well the volatility of oil prices, especially in what historians may one day call the beginning (1860-1920) and the end (1970-2040) of the industry. These two sixty-year periods are extremely volatile compared to the middle 50 years (1920-1970). In examining figure 2 it is important to remember that the global oil industry grew by 17,000% in the hundred years of the Twentieth Century (rising from 20 Mt in 1900 to 3.4 Gt in 2000 (Smil, 2000)).
Fluctuations in oil prices are also believed to trigger wide speculation (the act of buying a contract of oil to be delivered at a future date in anticipation of selling it at a premium) in oil financial markets and can potentially disrupt market dynamics by creating a high order of non-linearity and multiple simultaneous feedbacks between various interacting systems (Juvenal & Petrella; 2012). Given its role in destabilising economies, causing inflationary pressures, and signalling global imbalances, understanding oil price behaviour remains vital for understanding, national and industrial planning and the management of risks associated with possible future disruptions. Understanding oil price fluctuations are also crucial for analysing prevailing market conditions and planning for mitigating strategies that can minimise the risk of disruptions. The importance of non-linearities and multiple feedback loops between numerous actors and decision centres is characteristic of world oil markets. Given the complex interaction between these constituents and their combined impact on oil prices, simple analytical methods are less suited for explaining both the price formation as well as for analysing the system-wide impact of changes in specific parts of the system on key macroeconomic indicators. A careful analysis and an evidence-based study of various market and policy attributes that can impact future global oil exchanges is critical as it is likely to impact the course of energy policy direction in the future and reduce the risk of policy failures.

A system wide perspective of exchanges in global oil is provided in this section and its wider implications for emerging energy pathways is assessed by developing and testing a dynamic hypothesis for oscillatory oil price behaviour. System dynamics modelling methodology is a well-established method to study various aspects of oil exchange related to production, distribution and capacity expansion as well as other strategic aspects related to global oil markets and the geopolitics of oil.

**System Dynamics and SD Oil Models**

System dynamics represents a theory of system structure and has been used for identifying, describing and analysing multi-loop, non-linear feedback relationships for many decades (Choucri, 1979). It is particularly useful to this PhD research as it helps to study the long-term dynamic behaviour of complex systems. These system structures are represented in system dynamics models as stocks and flows, with causal mechanisms controlling their rates of change and feedback loops formulating various causalities. Complex real-world systems comprise of several interconnected feedback loops together with nonlinear interaction between the physical and decision-making structures (Forrester, 1970). The feedback loops of a system are mapped using causal loop diagrams and stock and flow variables. Details of SD approach and methodology are provided in Chapter 2.
As outlined earlier in chapter 2, system dynamics allows to both describe the relationship between variables as well as represent a problem; inputs are generated from feedback relations within the system, and the outputs of one period feed in as inputs for next; delays in a system represent lags—these can effectively enhance or dampen the stability of the system and usually explains why it often takes time for the effect of policy decisions to be felt; delays also determine the severity of ‘shocks’ and are responsible for the ‘overshoot and collapse’ behaviour demonstrated by many systems (Sterman, 2000). These delays are period of adjustments in the oil model, and are a key feature of global oil exchanges in the real world as in the oil market developed in this study.

Price movements are central to determining dynamic behaviour of resources and have been the basis of most global oil models since the 1970s. The dramatic oil price movements in the past have caused major structural changes like economic depression, transfer of capital from consumers to producers, and booms and bust in production and exploration sector (Morecroft & Marsh, 1997). Many different approaches have also been used to model oil. Some models are based on the estimation of price elasticity and income elasticity of oil demand, examples include Adelman’s (1982) model-based analysis (Psacharopoulos, 1987) and econometric models by the IEA and IMF. Many others base their work on price determinations on the pioneering work by British economist Harold Hotelling, based around the assumption that oil is an exhaustible resource, and it could, therefore, be treated as a financial asset commanding a premium over and above its immediate value, which increases overtime with intensified perceptions of its scarcity (Hotelling, 1931). However, in an era of supply abundance ushered by shale oil revolution, the assumption that oil is an exhaustible resource perhaps needs to be held with some degree of caution (Fattouh & Sen, 2013).

Many published detailed reviews of oil models can also be found in the literature ((Choucri & Heye, 1990); (Akopov, 2012); (Tao & Li, 2007); (Hosseini & Shakouri, 2016) (Al-Qahtani, et al., 2008), (Morecroft & van der Heijden, 1992); (Samii & Teekasap, 2010)). The existence of an extensive volume of SD-based work centred around oil dynamics establishes its suitability for analysing the long-term resource dynamics arising from multi-linear feedbacks and exchanges. A review of these models also establishes the appreciation and importance of key economic relationships that are vital for analysing geopolitical movements. Despite its proven suitability for carrying out robust analyses of future scenarios that facilitates an equitable, sustainable and secure allocation of scarce oil resources at an acceptable economic, social and political costs, a model that represent the exchanges and dynamics representative of modern global oil markets could not be found. This chapter attempts to fill this gap in literature by presenting a model that represents the dynamics of global oil markets as they currently exist, while analysing the impact of emerging oil dynamics on long-term energy policy objectives.
This section builds itself on the basic principles of oil price formation as an anchoring process that strives to establish a balance between demand and supply dynamics. Key formulations identified in the extensive modelling work by Nazli Choucri and her team at MIT in the 1970s serve as an appreciation of the analytical specifications of the model. As previously established in the work of researchers such as Choucri (1979, 1980), Morecroft (1997) and Sami & Teekasap (2010), price determination is the central element in analysing the costs and benefits of policy choices and have, therefore, been endogenously determined. These studies also suggest that any valid long-term analysis of resources must also be based on endogenous interactions between producers, consumers and market forces that regulate and manage the flow of these resources (through price control mechanisms mediated by markets players, government regulation or midstream operations) and must consider the political and economic costs to individual actors of the sub-system.

A dynamic model that incorporates these interactions together with associated sources of conflict can be instrumental in analysing impacts of policies for both the producers as well as the consumers. Furthermore, as the production, flow and transit of resources take place across regions, the analysis must also incorporate a global perspective. A complete analysis of all these interactions is essential to determine consequences of policies in producer countries over consumers, and vice versa, yielding invaluable insights for determining the efficacy of policy choices. The oil-model developed in this PhD research is guided by these central ideas that are key to oil market exchanges. Uncertainties in markets (through price-demand-supply movements), time delays, non-linear causal relationships and concurrent interactions between various oil sub-systems are incorporated to generate the system dynamics, which are subsequently used to assess the impact of various likely scenarios.

Key concepts of oil price formation and a closer undertaking on global oil markets trends and landscape is an essential prerequisite for determining the key attributes for the model and for developing the model. These details are reviewed in the following sections.

**Oil Market Outlook and Price Formation**

Oil is a political commodity (Penrose, 1976) and has been central to a number of key global economic and political decisions over many decades. Crude oil, together with its refined products, is the most widely traded commodity both by volume and by value (Stevens, 2005) and it has the highest energy content of all the fossil fuels. Despite some reduction in the last two decades, oil continues to be largest source of primary energy globally (34 percent in 2018), followed by coal (27 percent), natural gas (24 percent), hydro (7 percent), nuclear (4 percent) and renewables (4 percent) (BPSR, 2019). This section provides a review of the global oil market focusing on its fundamental characteristics.
Global Oil Markets

Oil prices impact all the economies of the world in a characteristically unique way. From an oil producer’s perspective, revenue from oil exports remains vital to their economic development and growth rendering them vulnerable to price volatilities. Consumer countries benefit from oil price drops, but get impacted by fluctuations in the quantities of oil supplied by exporting countries, thus impacting their economic and political stability (Allsopp and Fattouh, 2013). Oil price fluctuations have, therefore, justifiably drawn much attention from governments, financial institutions and the energy industry.

The demand-supply paradigms that have historically underpinned the oil markets have undergone structural shifts since the heyday of interest in oil industry SD modelling in the 1970s and early 1980s. Since those times there has been explosive demand growth in developing countries in the east, led by China, and on the supply side there has been the shale oil revolution in the US. Furthermore, global supply and demand patterns responded sharply to the economic slowdown arising from the COVID-19 global pandemic. The EIA has reported that the global consumption of oil stood at 92.2 million barrels per day in 2020, declining by 9 percent or, 9.0 million barrels per day compared to 2019. EIA’s Short Term Economic Outlook (2021) reports that the combined effect of reduced oil demand, as a result of global pandemic (notably from reduced jet fuel consumption), and an easing of geopolitical tensions caused Brent crude oil spot prices to crash from around $67 in early January 2020 to $18.38 in April.

However, as consumption increased in the latter half of 2020, coupled with reduced production from OPEC and partner countries (OPEC+) and U.S. crude, inventories fell and oil price recovered to a monthly average of $50 per barrel. An upsurge in global growth, driven by collective global recovery from the aftermaths of the global pandemic, is expected to drive a robust increase in oil demand and to re-balance the global oil inventory levels adding significantly to upward oil price pressures. The EIA expects that Brent prices are likely to experience downward price pressures over the next two years and the prices may average $59 per barrel, depending, among other factors, on future production decisions by OPEC+, the responsiveness of U.S. shale production to higher oil prices, and rate of oil demand growth (EIA, 2021). The model presented seeks to emulate such behaviours.

Depending on the pace of economic growth and strategic decisions by major players guided by longer-term drivers of growth, the IEA expects global demand for oil to grow at an average annual rate of 1.2 million barrels per day, reaching 104.1 million barrels per day by 2026, up 4.4 million barrels per day from 2019 levels (International Energy Agency, 2021). Emerging and developing economies, led by China and India, underpinned by their increasing population and income growth
are predicted to be the strongest drivers of global oil demand growth. Whether there will be enough supply from producers to meet the rising demand would have been a major consideration in the past. But the upsurge in oil supplies with the discovery of tight oil in US has shifted the narrative away from resource scarcity towards resource abundance. These uncertainties in the supply-demand dynamics can, as a direct consequence, create widespread speculation and fluctuations in oil prices. Table 4.1 shows the top crude oil producers and consumers of the world.

**Table 4.1: Top 10 Crude Oil Producers (in 2020) and Consumers in 2018**

<table>
<thead>
<tr>
<th>Country</th>
<th>Million barrels per day</th>
<th>Share of world total</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>18.60</td>
<td>20%</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>11.01</td>
<td>12%</td>
</tr>
<tr>
<td>Russia</td>
<td>10.50</td>
<td>11%</td>
</tr>
<tr>
<td>Canada</td>
<td>5.29</td>
<td>6%</td>
</tr>
<tr>
<td>China</td>
<td>4.93</td>
<td>5%</td>
</tr>
<tr>
<td>Iraq</td>
<td>4.16</td>
<td>4%</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>3.79</td>
<td>4%</td>
</tr>
<tr>
<td>Brazil</td>
<td>3.78</td>
<td>4%</td>
</tr>
<tr>
<td>Iran</td>
<td>2.81</td>
<td>3%</td>
</tr>
<tr>
<td>Kuwait</td>
<td>2.87</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total top 10</strong></td>
<td><strong>94.24</strong></td>
<td><strong>72%</strong></td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>100.66</strong></td>
<td><strong>72%</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Country</th>
<th>Million barrels per day</th>
<th>Share of world total</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>20.51</td>
<td>20%</td>
</tr>
<tr>
<td>China</td>
<td>13.89</td>
<td>14%</td>
</tr>
<tr>
<td>India</td>
<td>4.77</td>
<td>5%</td>
</tr>
<tr>
<td>Russia</td>
<td>3.88</td>
<td>4%</td>
</tr>
<tr>
<td>Japan</td>
<td>3.79</td>
<td>4%</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>3.08</td>
<td>3%</td>
</tr>
<tr>
<td>Brazil</td>
<td>3.06</td>
<td>3%</td>
</tr>
<tr>
<td>South Korea</td>
<td>2.57</td>
<td>3%</td>
</tr>
<tr>
<td>Canada</td>
<td>2.53</td>
<td>3%</td>
</tr>
<tr>
<td>Germany</td>
<td>2.33</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Total top 10</strong></td>
<td><strong>60.40</strong></td>
<td><strong>60%</strong></td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>11.37</strong></td>
<td><strong>11%</strong></td>
</tr>
</tbody>
</table>


Unlike other traded commodities, market mechanisms do not solely determine oil prices, as highlighted above. Some of the major global oil trade movements seen in 2018 have been presented in Figure 4.3. According to Fattouh (2010), expectations from, or perceptions of, future market fundamentals have a key role in oil price formation. He posits that price bubbles may result as a consequence of changes in supply-demand dynamics away from their basic essential values (Fattouh, 2010). A closer appreciation of the basic principles of oil price formation helps to better understand the trajectory of oil price movements and such ideas are described in the following section, and again, our model is developed so to mimic these realities.
Fundamentals of oil price formation

Choucri (1979, 1980), laid the foundation of the principles for model-based determination of demand, supply and price specification of the oil markets. Details on the modern-day mechanisms of oil price formation can be found in the work by Fattouh (2009, 2011, 2016, 2018), Energy Charter Secretariat (2011), Barsky (2014), etc. These studies, besides providing an understanding into the oil market structure and an insight into the dynamics behind global oil exchanges, also highlight the significant changes that have occurred in oil markets since 1980. The modern-day exchanges, characterised by financial instruments such as forward markets, swaps, futures, options, etc., differs markedly from those that existed in the 1970s and the first half of the 1980s. This chapter aims to develop a model that helps to analyse the modern-day exchanges in global oil markets anchored around oil prices.

Crude Oil, Benchmarks and Transactions

Crude oil is a global commodity, traded since the inception of modern oil industry in the 1860s (ECS, 2011). An understanding of the unique nature of crude oil is crucial to understanding oil pricing mechanisms, which is determined by a range of factors influencing oil supply-demand dynamics, such as by the government policies, geopolitical conflicts, global economic growth and strategic influences by stakeholders.

Crude oil is the commercial term for raw petroleum, as extracted from the ground. It is a naturally occurring unrefined liquid comprising hydrocarbons with different chemical compositions. It is found in sedimentary rock deposits and basins within the earth’s crust. Petroleum (literally ‘rock oil’) has formed from the decomposition of aquatic animals and plants buried at high pressure for hundreds
of millions of years (Everett and Crabbe, 2012). The presence of geological traps preventing the lateral migration of the petroleum away from the reservoir is an essential prerequisite for the accumulation of crude oil reserves (Everett and Crabbe, 2012: 214). The differences in chemical arrangements of branching chains account for differences in properties of different grades of crude oil. Crude oils can vary significantly based on their region or oil field of origin and showcase unique properties.

Over a hundred crude grades are traded in markets around the world. The total value of the crude is determined on the basis of the total value of the products processed from crude, also sometime referred to as the gross product worth (or GPW). While GPW may be believed to define the upper limit of crude prices and interact with the prices of products, it does not necessarily set the price of crude oil (ECS, 2011). Benchmark crudes act as points of reference for other crudes of similar grades.

West Texas Intermediate (WTI) and Brent crude replaced Arabian Lights in the late 1980s, acting as the two globally dominant benchmark prices. There are, however, significant differences between WTI and Brent crudes and the two are often seen trending at significantly different prices. A possible explanation can be their perceived role in their respective markets. North Sea Brent is produced by several producers yielding it a higher degree of security of supply, greater diversity of sellers and broader acceptance by consumers. Owing to higher volumes of production from across multiple oil fields, there is greater market trading liquidity for Brent. WTI, in contrast, is produced in lower quantities has a landlocked delivery system and is located unsuitably for a benchmark grade for various international trading markets. Nonetheless, WTI has been a huge commercial success since it was selected for the launch of crude oil futures on the New York Mercantile Exchange (NYMEX). It has since become the leading US benchmark price. It is essential to highlight that WTI has the advantage of faster response and an almost immediate reaction to market volatility. However, given the linkages between Brent and physical markets, arguably Brent crude reveals better the supply-demand dynamics of the market (ECS, 2011).

Saudi Arabian crude is not traded in the spot market but directly under long-term contracts. Dubai and Oman together play the role of a Middle East benchmark price and play an important role in retroactive pricing formula by large producers of the region such as Saudi Arabia, Iran and Kuwait. Urals grade crude comprises of crude from oil fields from Russia and neighbouring region, which are mixed and transported by Transneft’s pipelines. The East Siberia-Pacific Ocean (ESPO) Oil Pipeline

---

5 Crude oils originating from North Sea and North Africa tend to be of lighter fraction and sweet, i.e. containing lower sulfur content; whereas the crude oils from Venezuela and some Middle East countries may be heavier, sour-with higher sulfur content and containing unwanted chemical impurities (Boyle, 2003; 225). The American Petroleum Institute (API) standard is commonly used to measure crude gravity, with heavy crudes falling under the API 22° range, light crudes under API 33°.
was laid by Russia to transport its crude for market trading into newer markets (ECS, 2011; Gyagri et al., 2017).

While most of the crudes are marketed via ports, some inland markets also exist. Crude oils on the North American continent are traded via inland markets. Some popular regional crudes include Malaysia’s Tapis, Indonesia’s Minas, Nigeria’s Bonny Light and the twelve OPEC crude grades that make up the OPEC Basket (ECS, 2011).

Crude Oil Pricing

**Historical context:** Oil prices at the start of oil industry in the early 1850s (in Titusville, Pennsylvania, US) fluctuated violently based on the discovery of new oil wells and production capacity of existing oil fields. Since its establishment in 1870 by John D. Rockefeller, the Standard Oil Company had an almost total control on the market before it broke-up in 1911 into a number of smaller companies such as Exxon, Mobil and Chevron (ECS, 2011). Elsewhere in the world, Royal Dutch operated in Indonesia in the 1890s as an oil producer, Shell Transport and Trading operated in Russia and Far East as distributors and sellers of kerosene. They later merged as the Royal Dutch/Shell group in 1907. By 1920 Exxon, Anglo-Persian (later became British Petroleum, BP), Royal Dutch/Shell, Mobil, Chevron, Texaco and Gulf Oil dominated the bulk of global oil business. These seven companies were popularly referred to as the Seven Sisters, or Majors and played a critical role in controlling oil prices through a somewhat cartel agreement popularly known as Red Line Agreement or Achnacarry Agreement in 1928 in the aftermaths of oil price crash after World War I. Crude oil prices, at the time, were limited to include the internal transfer prices of the Seven Sister companies to minimise the rent owed to the oil producing countries. Because of the common prevalence of isolated arms-length sales of refined products until 1960, crude oil price data is deemed irregular and analysed with a degree of caution. The plunge in oil prices in the 1950s brought about a further drop in already low oil producing countries’ tax revenues leading to the formation of Organisation of Petroleum Exporting Countries (OPEC) in 1960. OPEC, at the time of its formation, comprised of Venezuela, Iran, Iraq, Kuwait and Saudi Arabia, and in the decades that followed somewhat changed the nature of oil market dynamics. The first oil crisis in 1973 occurred as a result of unilateral price increase by OPEC from 3 to 12 $ per barrel and the second oil crisis in 1979 took place after the Iranian revolution when the oil prices shot up from 12 to 30 $ per barrel (ibid).

The emergence of a market-related pricing system in the 1980s was a response to the supply disruptions from the oil crises of 1973 and 1979. The 1980s saw a new chapter in the history of oil price formation. The disruption brought about by the two oil crises had created widespread nervousness among crude oil buyers, who were ready to pay higher spot prices than the official
prices to secure the desired stock of oil supply. This signalled a shift away from OPEC-administered pricing system and the emergence of market-based oil pricing governed by the dynamics of supply and demand fundamentals (Fattouh, 2011; ECS, 2011). Crude oil, in more recent times, has been said to have acquired the traits of a financial asset attaining a complex-market structure that comprises of spots together with physical forwards, futures, options and other derivative markets referred to as paper markets (ibid). However, crude oil (unlike pure financial assets) also has a physical aspect to it as it can be consumed, stored, and traded in physical quantities at agreed prices between various transacting parties. The spot prices reflect the supply-demand dynamics of markets and serve as an anchoring point for prices in the futures market (Fattouh, 2010). It is important to highlight that physical realities and psychological concerns both play important roles in oil market price formation.

While the oil markets have, in recent decades seen the emergence of a number of financial layers such as forward markets and financial instruments such as: swaps, futures, and options, unlike other pure financial assets, the physical dimension of crude oil market lends an anchoring point for expectations of market fundamentals. A brief account of modern day oil-trading is provided in Box 4.1. Consequently, in principle, through the process of arbitrage the future market prices must converge to the spot prices that underlie the physical supply agreements. In the context of physical delivery of oil, contracts are negotiated bilaterally with price agreements determined by formula pricing becoming the basis for price determination (Fattouh, 2010). Fattouh (2011) provides a detailed review of the anatomy of oil pricing system detailing out various specific components. The formula pricing system allows for crudes to be price-indexed to benchmark crudes and can be priced at a discount or a premium based on quality and relative demand-supply conditions. Fattouh (2010) specifies that for a crude oil of variety x, the formula pricing can be determined as PX = PR ± D, where, PR is the benchmark crude price, and D is the value of the price differential. Fattouh’s formalism aligns with the view that, aside from fixed offsets specific to each variant benchmark, there is indeed a single global oil price. The model developed in this research is consistent with that well established assumption. The global oil market has both financial and physical layers, and it can be difficult to isolate the two. It can also be observed that while the spot price of oil can reflect the market dynamics, the true fundamentals of the market are determined by the interaction between various participating players involved in the overall global exchange of oil at various levels impacting its production, processing, transportation and the existing social, economic and political landscape impacting its uptake in consuming markets.
Oil is traded between buyers and sellers through contracts negotiated between various parties either physically or electronically. The first oil futures market seems to have emerged in the form of pipeline certificates in response to oil price volatility in the US in the 1860s. The following three decades witnessed the emergence of many exchanges actively trading crude futures in the US, Canada, and Europe. The New York Mercantile Exchange (NYMEX) had its first new future’s contract in heating oil in 1979 followed closely by the International Petroleum Exchange (IPE), now known as Intercontinental Exchange Inc. (ICE), in London in 1981. IPE also allows for a unique delivery system popularly known as exchange of futures for physicals (EFP), whereby a futures contract can be cancelled out with a spot contract. Some of the prominent spot markets for crude oil are Rotterdam for Europe and New York for the US, the main markets for petroleum products are located in Northwest Europe for ARA (Amsterdam, Rotterdam and Antwerp), the Mediterranean, the Gulf, Southeast Asia, Gulf of Mexico and US East Coast. Besides Brent and WTI, other grades with strong spot trading are: Ekofisk, Forties, Osberg (from the North Sea); Urals from Russia; UAE’s Dubai; Indonesian Minas; Malaysian Tapas; Alaska North Slope (ANS) and West Texas Sour (WTS) from the US; and Nigerian Forcados and Bonny Light.

Spot transactions occur as an over-the-counter (OTC) negotiation between parties over recorded wired communication. While such transactions lack transparency and may a higher degree of counter party risks, they are easier to draw-up as they do not require the specifications needed by an exchange. Spot market participants for crude oil trade include refiners and producers with traders playing the role of middlemen buying cargoes from sellers and reselling them to end-users. Negotiations in most spot crude sales are governed by spread trading mechanism whereby negotiated prices are based on price differentials between the traded crude and the benchmark it is indexed to. Because the negotiated prices are normally only privy to negotiating parties, publications that list price records play a crucial role in ensuring fluid trading. To hedge the risk of high price volatility generated by spot trading, forwards and futures markets were established. Forward markets operate in a more standardised manner than spots. Three price quotation namely ‘dated Brent’, ‘fifteen-day Brent’ and ‘ICE Brent’ can be seen around Brent forwards in Europe. Cargoes within fifteen-day availability handled by spot markets are called dated-Brent; the more distant deliveries are called fifteen-day Brent, while ICE Brent is Brent traded on the ICE futures market. A futures contract, on the other hand, is an agreement to buy or sell an asset at a specific future time at an agreed price. The value of a futures contract is derived from the value of its underlying assets, hence the name derivative. Both forwards and futures are derivatives, and while forwards are traded on an OTC market, a futures contract is traded in more organised markets of exchange through standardised contracts. Futures markets are becoming increasingly popular among oil companies and traders seeking to hedge against price fluctuations. It also offers a cost-free mode of exchange as the position holder does not have to take physical delivery if a position is cancelled by the opposite position. In contrast, options can be traded both in the OTC market and on the exchange, and require an up-front payment. The two basic types of options are call and put, which can each take a long and short position. A call option is the right to buy and put the right to sell an underlying asset by a certain date (known as expiration date or maturing) for a price (known as exercise price or strike price). A long position is assumed when a party agrees to buy an asset on a certain future date at a specified price, and conversely, it assumes a short position if it decides to sell an asset on a future date for an agreed price. Theoretical options premiums are determined using models, most prominent being the Black and Scholes model, named after Fischer Black of Goldman Sachs and Myron Scholes of Long-Term Capital Management (ECS, 2011).

A System Dynamics based representation of oil market fundamentals

With the existing interdependencies of multi-actor networks and their feedback, global oil exchanges can be classified as complex systems which consists of various feedbacks interacting together to generate dynamics in systems (Sterman, 2000). The essential aggregate features in a global oil exchange are supply, demand, and price relationships. These aggregate dynamics, in turn, are further determined by extremely complex feedbacks between various social, economic, and political factors, which, for the sake of simplicity, have been excluded, other than at a high level of
generality, from this study. It has been further established in the section on oil price mechanism that the structure of oil markets stays in a constant state of flux, and the process of price determination constantly adjusts to the changing dynamics of supply and demand. This study endogenously models oil price volatility and analyses the macro-dynamics of oil exchange without attempting to make predictions.

A simple causal-loop diagram has been developed to highlight the relationship between supply, demand, price and market perceptions, and is shown in Figure 4.4. The relationships and exchanges shown in the figure determine the feedbacks that guide the model-based analysis undertaken in this work to illustrate the modern-day market fundamentals.

The system described by the causal loop diagram can be seen to be dominated by a number of balancing loops. The system can therefore be expected to exhibit goal seeking behavior. Additionally, adjustment delays regularly take place in the system as components of the system adjusts to disruptions and changes. Based on the goal seeking behavior of the system, coupled with delay, the oil prices may exhibit oscillations, as described earlier in Figure 2.4. The behavior expected by the system described by the causal-loop-diagram, is also shown in Figure 4.4(a).

The SD-based optimisation structure called hill-climbing proposed by Sterman (2000) is effective in discovering the optimal operating points that can reach the desired outcomes through a series of floating goals and adjustment. The heuristic advanced by the hill-climbing model applies well to represent the oil price adjustment process. In a general hill-climbing structure, the desired state of a
system is anchored on the current state, which in turn is adjusted by various external pressures. Sterman’s (2000) hill-climbing structure can be applied to oil price determining process and can be used to determine oil price \( P \), \( P = \text{INTEGRAL\ (Change\ in\ Price,\ Pt0)} \); Change in Price = \((P^- - P)/\text{PAT}\); \( P^* = P^* \cdot \text{Effect\ of\ Demand\ Supply\ Balance\ on\ Price}\); Effect of Demand Supply Balance on Price = \( f(\text{Demand/Supply}) = (\text{Demand/Supply})s \); and \( S \) is the sensitivity of price to demand/supply balance.

The formulation establishes the relationships between supply, demand and price, whereby as prices rise the demand for oil falls and supply rises. In stable conditions or in equilibrium, price remains at a level that can principally balance supply and demand. The oil-model for this study is also initiated in equilibrium. But supply and demand of a commodity like oil is also impacted by expectation of future outcomes and sudden shocks. As supply and demand dynamics change, price of oil \( P \) adjusts to an indicated price over an interval given by Price Adjustment Time (PAT). If demand exceeds supply, the indicated price rises, and with it the actual price. Conversely, price falls as long as supply exceeds demand.

Based on the causal loop diagram shown in Figure 4.4 and the hill-climbing price determination formulation, a model comprising of feedbacks between supply, demand and price components in the oil markets is developed. As highlighted in the sections above, nonlinear relationships are fundamental components and characteristic to oil market dynamics, and are critical components in the model. The model relies on these non-linear relationships to represent the effect of price on selected parameters, which are calculated from observed market trends.

The supply side feedbacks consist of conventional (OPEC and non-OPEC) and shale oil supplies; demand side dynamics are dominated by US, China, India and the aggregate demand of the rest of the countries and the price dynamics consist of the impact of market sensitivities and the impact of oil balance perceptions and inventory coverage on oil prices. The feedback structure of price formation structure used in the model is presented in Figure 4.5. The balancing Price Adjustment loop adjusts price to the indicated level, which in turn is based on the current price. Indicated oil price adjusts through the reinforcing price discovery loop.
Figure 4.5: A simplified stock and flow diagram of oil price determination process

Model Structure Validation using a Partial Model Test: The price dynamics component of the model, shown in Figure 4.5, forms the core structure of the model. It was simulated to conduct a partial model test to demonstrate the intended rationality of the price setting process and determine the robustness of the structure. The oil demand/supply coverage variable in the model represents the supply chain of the oil markets and remains constant under stable market conditions indicating that there are no fluctuations in the oil production, processing and transportation systems. The model was initiated with the Brent price of $108 per barrel, as reported for 2015 by the BP Statistical review. The goal of this structure is to model price setting consistent with the relevant information available to and behavioural decision process of actors involved in price-setting process. The model, more generally, has been calibrated from real data from British Petroleum’s Statistical Review (BPSR) of World Energy (2017), and simulations are run for 50 years. According to BP’s annual statistical review of world energy, based on the world proved oil reserves of 1687.9 billion barrels in 2013, an estimated 53.3 years of oil is left at the current rate of production. Consideration of long-term upstream resource depletion is excluded from this modelling.

Simulation results indicate that oil prices are highly sensitive to adjustment time during which changes occur in market perceptions about oil demand/supply coverage or the perceived stock of oil supplies available to meet the forecasted demands. Oil prices respond to changes in perception with a delay, as it takes time for the markets to gather, report and respond to disruptions. Inventory coverage is held constant, and the oil price adjustment time is taken to be 6 months for simulation runs. For simplicity, perceived coverage is modelled with a first order smoothing. The strength of the
effect is determined by the value assigned to the ratio Sensitivity of Price to Oil Demand/Supply Coverage. A delay formulation between demand and perceived demand is introduced factoring in an exogenous variable that accounts for the delay in time to form expectations and make required adjustments in demand by adjusting factors of production.

Oil price, in the partial model test, follows a state of equilibrium when Sensitivity of Price to Oil Demand/Supply Coverage = 0, but when this value is 1, then price is anchored solely on market perceptions of the impact of demand/supply shortage of oil. In reality, however, oil prices are effected by both market perceptions as well as physical disruptions. If demand and supply remain in balance, the system will move exponentially to a new price such that Indicated Price = Oil Price. As long as Sensitivity of Price to Oil Demand/Supply Coverage > 0, the positive price adjustment loop is dominated by the market perceptions and the system converges to a state of equilibrium. The key formulation of price setting as an anchoring and adjustment process aligns with the literature on oil market price formation. However, there are constant fluctuations in supply and demand dynamics arising as a result of emerging geopolitical tensions, changes in political priorities and levels of economic growth in the biggest demand centres, and oil markets do not linger in a state of demand and supply balance. It is therefore essential to incorporate such disruptive issues in the model to represent realistically the market fundamentals with any degree of success.

Within the scope of this model the impact of price on levels of production and consumption for various dominant producers and consumers can be analysed. The model also helps assess the effect on oil market dynamics of interactions between the oil price and key macro-economic parameters. One such parameter is the impact of level of economic growth. An input variable has been included in the model to introduce demand disruptions enabling study of emerging behaviours of modelled parameters and the impact of demand disruption on other key variables. A formal model structure showing these exchanges is presented in Figure 4.6.
Figure 4.6: Formal model structure representing the nonlinear global exchanges between the price, supply and demand of oil
Scenario Description and Analysis of Model Behaviour

Assigning constant values to parameters such as initial oil stock, factors of production and consumption, a state of equilibrium has been achieved, as shown in Figure 4.7. But, noting long-term considerations, such as geological resource depletion which are not accounted for in this modelling, such a state is only likely to exist in simulated conditions such as during a model run with disruptions blocked.

![Figure 4.7: Supply, demand and price equilibrium under controlled conditions generated by the model](image)

Figure 4.7 shows a gentle and straightforward convergence towards equilibrium from nearby initial conditions. It shows system stability in the absence of external shocks or disturbances. To analyse the impact of various feedbacks on oil market dynamics different scenarios are introduced, relating to different forced model inputs as might emerge as a consequence of, for example, market disputes, technical failures, wars or international public policy push.

To replicate the realities of oil markets, an input variable is included to introduce demand disruptions in the model and to study the emerging model behaviour and its impact on other key variables. Significant insights into oil market dynamics are generated by the model, as shown in the subsequent sections. There are, however, some caveats in this model on account of its simplified structure. A number of factors that can potentially impact production, supply and consumption of oil, and significantly impact oil price dynamics have not been factored into the model. The purpose of this model, as indeed most other SD models is not to make predictions. The modelled-results, however, generates significant insight into the impact of varying oil-price levels on emerging market conditions and oil dynamics in the future.
Scenario descriptions

To analyse the impact of various feedbacks on oil market dynamics different scenarios, related to different levels of prices, demand and supply dynamics, are analysed. Scenario 1 considers a set of supply-side shocks. Scenario 2 explores the possible consequences of growing pressures of decarbonization, especially those affecting demand effectively in OECD countries.

Several other scenarios can also be generated using this model based on the need to assess a unique pathway for oil markets. But the scenarios described above provide sufficient details for the purposes of this study.

Price dynamics

Price changes affect both the amount of oil demanded and quantity supplied, which in turn impacts price. On the supply side there are delays associated with adjustments to ramp the production levels up or down, based on demand signals. Several short run demand adjustments to price signals occur, while supply adjustments usually take longer to materialise as they involve lasting changes to the entire supply chain. These adjustments, however, are not instantaneous and involve significant time lags. Price at $t_1$ leads to a specified quantity of oil demanded, which through signals and interactions and over various decisions by agents involved lead to an amount supplied. This amount is constrained by previous demand patterns and prevalent factors of production involving key components such as labour, capital, resources, etc. The modelled oil price trajectory responding to adjustment delays is shown in Figure 4.8.

Figure 4.8: Simulation results for oil price dynamics responding to specified time lags. (Note the damped oscillatory behaviour. The period of oscillation tracks the magnitude of the Oil Balance Perception Time.)

4.8(a): Oil Balance Perception Time = 2 months [Demand adjustment Time=1 year; Price Adjustment Time = 6 months] in the ‘Reference Scenario’ test.

4.8 (b): Oil Balance Perception Time = 18 months [Demand adjustment Time=1 year; Price Adjustment Time = 6 months] in the ‘Reference Scenario’ test.
Oil price in the model shows significant sensitivity to various adjustment times. Three fundamental time parameters are included in the model: Price Adjustment Time; Demand Adjustment Time; and Oil Balance Perception Time. Of these the quickest is the Price Adjustment Time and in modern markets with high levels of market automation this step could in principle be close to instantaneous for a single market player. Nevertheless, it is posited that such an adjustment actually takes some time to hold at a global level. Oscillations in oil prices are seen to occur when adjustment time is lowered. The amplitude of oscillation in oil price generated by the model depends on the intensity of time lag. Given this model is intended to explore long-term trends and over a 50-year range, price-adjustment time is set to (0.5 years) or 6 months. When the price adjustment time is halved, the frequency of oscillations increases and it takes less time for the amplitude of oscillations to dampen towards a new equilibrium, as shown in Figure 4.8. Conversely, when the adjustment time becomes longer, it takes longer for oil prices to attain a stable state. The sharp volatility in oil prices simulation results occurs as results of changing perception of available supply coverage for varying levels of demand, and is consistent with the historical oil price movements. The sharp movements in price movements seen in the simulation results analysed provide an explanation for the repeated fluctuations observed in real oil prices.

It is worth highlighting that as the model developed is an aggregate model, sharper minute-by-minute variation, as observed on electronic exchanges, is not modelled.

The next time parameter is the Demand Adjustment Time, which involves supply chain considerations and can be slow in real life to adjust to new price realities. These demand side considerations also cascade up to affect supply chain steps upstream of refining concerning resource extraction and even exploration. The demand adjustment time is set at 1 year in the model. Finally, the oil balance perception time –relates to the time taken for data-driven fears to transform into demand response decisions. It is a quicker process than the supply chain issues shaping the Demand Adjustment Time and, it is set at 6 months (0.5 years).

Figure 4.8 illustrates the characteristic damped oil market oscillations that are seen throughout the modelling when hit by a severe shock. Each figure shows the current oil price and the indicated oil price which is key to the oil model’s price formation process. These prices are shown per barrel in USD with a significant y-axis offset. The third curve, change in oil price, relates to the other two but it has different dimensions as it represented the flow of change in price, and it is shown much magnified and on a scale that spans negative and positive values. In figure 4.8B one can see that the frequency of the oscillations in price and price change are not the same. The only difference between figure 4.8A and 4.8B is that the Oil Price Perception time is six times slower in the case of
figure 4.8B. While this change dramatically slows the oscillation frequency that frequency is not simply the same as the Oil Price Perception Time. When the Oil Price Perception Time is 2 months the oscillation period is roughly 3.5 years and when it is 18 months the oscillation period is roughly 13 years. The damping rate is far slower and appears unaffected by this parameter.

With an awareness that the model tends to manifest a damped oscillation SD archetype, a set of supply-demand shock scenarios relating to different forced model inputs as might emerge as a consequence of external shocks such as market disputes, technical failures, wars or international public policy push are considered in the next section. These scenarios are designed to analyse the impact of various feedbacks on oil market dynamics. The first is a pure supply reduction shock such as might be caused by OPEC action, a war in the Persian Gulf, UN sanctions on a major producer or a simultaneous combination of multiple factors. The second scenario explores the possible consequences of growing pressures of decarbonisation, especially those affecting demand effectively in OECD countries. In each case the focus is on the consequences for global oil prices and aggregate global demand with an intention to examine the consequences of relatively simple supply and demand side pressures. The purpose of this modelling is not to predict future oil prices or levels of production or consumption, rather it is to use SD in order to assess the types (termed ‘archetypes’ in SD discourse) of market dynamics that might be expected to occur in markets under stress and to consider the resilience of markets and the SD modelling technique. (Systems archetypes are a class of tools offered by systems thinking methodology for diagnosing problems and to capture ‘common stories’ or dynamic phenomenon occurring repeatedly in diverse settings, details in Kim (1992).)

**Scenario 1: Oil Production Shock**

This scenario explores the changes in oil market behaviour when the production rate of a set of dominant aggregate producers, in this case OPEC members, suddenly decreases. It is widely believed that events in the Middle east are strongly correlated to political and economic events globally through their effect on the price of oil, which is influenced by varying the production and supply of oil (Barsky and Killian, 2004). The state of oil-market directly impacts the economies of countries reliant on petrodollar (or, any U.S. dollar paid to oil-exporting countries in exchange for oil; the term has been loosely used to indicate reliance on oil trade). An oversupply-driven-low-oil-price regime is not conducive to OPEC producers, who may find it increasingly difficult to sustain their economies in the age of competitive oil, even forced to run large fiscal deficits and cut back on essential welfare provisions, which would have ripple effects of global oil production and prices. A test STEP input is introduced in year 20 with supply restoration over two years. In the model OPEC production cuts of
the magnitude 10%, 20% and even 50% is introduced. The simulation results of changes in model behaviour to a STEP input are presented in Figure 4.9.

![Figure 4.9: SD model demand behaviour in response to a sudden reduction and then restoration of supply in years 20 and 21. Different levels of reduction are analysed (10%, 20% and 50%)](image)

Figure 4.9 illustrates the response of the global oil system to supply-side shortfall shocks of differing magnitudes lasting two years (in years 20 and 21). The oil stock is initially in equilibrium for the first 20 years, since the demand and consumption rates are deemed to be in balance. It then starts to decrease due to STEP input taking effect. In the case of a 10% reduction in OPEC supply, demand reduction consistent with normal price elasticity behaviours is seen. By 20%, however, archetypal oscillatory effects start to manifest themselves and these endure far beyond the initial 2-year shock. In the 50% case a massive reduction in demand is immediately triggered. Stocks in the system are drained and non-OPEC and US Shale production adjusts in response to price signals. Figure 4.9 shows how demand falls steeply until around year 24 it discontinuously falls no further. It is interesting that the demand curve continues to show a discontinuous trend even when the actual upstream supply shock is already over and full OPEC production is enabled once again. This flat demand feature in the 50% case is attributed to a sharply increasing oil price during this period. A properly functioning market might intuitively be expected to exhibit smoother behaviours without exhibiting such discontinuities, but the realities of agent decision making in real markets can give rise to market failure. The 50% OPEC-cut is held to represent a type of market failure, for the market that is implemented in the model.

Sensitivity testing of the behaviours revealed in figure 4.9 confirms that the length of time where total oil demand is flat in the 50% case is determined by one key parameter - the Demand Adjustment Time. The longer that time is, the longer the extent of the flat feature seen in figure 4.9. The Demand Adjustment Time determines the flat demand period, but the flat demand lasts longer
than the Demand Adjustment Time. In the case where the Demand Adjustment Time is set at unrealistically low, essentially instantaneous, level then the discontinuities and flat feature entirely disappears. In that case the market would appear to operate effectively, but it is not a realistic situation. The oscillations observed in various parameters are due to the existence of various delays with which adjustment in market mechanisms and physical adjustments in oil supply chain takes place. The model is premised around the assumption that price acts as an anchoring point and strives to balance any inequalities in the market towards the most efficient allocation of oil resource, a striking feature of the modern-day oil markets.

In figure 4.10, the associated behaviour of the oil price in each case, corresponding to figure 4.9 is presented. And although anomalies in the demand profile in the case of the 50% supply-reduction-shock occurs, price behaviours remain smooth. With a restoration of full supply pent up demand returns (after delays) and there is a strong increase in demand before oscillatory behaviours is seen, as seen cleanly in the 20% case.

Figure 4.10: Oil price in the supply side shortfall shock scenarios presented in figure 4.9

Figure 4.10 shows that with a 10% supply shortfall shock, prices rise as part of the price demand elasticity discussed in connection with figure 4.9. Oscillations mirroring those seen in demand are also visible in oil prices over the relevant timescales in each case (more marked in 20% and 50% reduction). In Scenario 1, since oil price starts to increase as soon as the supply-side shock input steps in, the OPEC production rate increases accordingly. Both conventional and unconventional oil production rates are impacted by sustained increase in oil prices, and therefore demand remains depressed in response to the supply shock. In the case of the 50% shock, even though the demand response indicates a discontinuous inability to match supply with demand (abrupt dynamic responses) the model indicates a smooth evolution in price. As also illustrated in figure 4.9, with a 50% supply side shock the oscillatory effects persist for nearly 20 years. It is also interesting to see the impact of the shock on long-term demand. In every case long-term equilibrium demand reduces, significantly in the case of a 20% or 50% shock.
This is consistent with a real-world market where, as a result of an extreme two-year shock, end-users could be expected to fuel switch away from expensive and insecure oil and also that they might act to improve energy use efficiency measures. Some physical adjustments of global oil infrastructure can take decades and may therefore result in lasting changes. Once the crisis is over the global oil market is smaller and a new supply–demand equilibrium is established at a new price point. In response to the oil-shocks of the 70s, which severely impacted India’s balance of payments and external financing at the time—given high import bills for petroleum, the use of indigenous coal and hydroelectricity was found cheaper; triggering a strategic shift marginalising the use of oil and emphasising coal usage in electricity generation (Chikkatur, 2008, pp. 30-31). Concerns over energy security can result in renewed efforts to develop diverse energy portfolio. Once the crisis is over the global oil market is smaller and a new supply-demand equilibrium is established at a new price point.

It can be argued that through these corrective behaviours, oil prices, act as an invisible hand that repositions oil markets into a self-correcting or a balancing trajectory. These corrections, however, occur over longer timeframe. Over a shorter term, the impact of shocks or the perception thereof can be dramatic and may generate a wide variety of corrections and responses from the relevant stakeholders. The following section will consider a particular form of oil demand decrease scenario. Here, the focus will move away from a short sharp shock, rather the focus will shift to an enduring shift – an energy transition.

**Scenario 2: The Climate Response**

Climate change has emerged as one of the most pressing issues globally with widely accepted irreversible environmental and social implications at a global scale. This scenario imagines a world comprising four oil consuming regions consistent with the approach outlined in Figure 4.4. There is consensus that immediate action is needed to mitigate the harmful effects of climate change, which includes, among other things, a significant reduction in fossil fuel emissions. The growth in oil consumption by India and China⁶ in response to low oil prices is a likely future possibility suggested by many oil industry analyses (BP; IEA; EIA). Such a future pathway is extremely concerning to a climate-conscious global community.

Any number of pathways to achieve the desired level of CO₂ emission reductions may unfold depending on the level of feasible demand reductions, and the local political and economic context, prevalent at the time, within various countries. Within the scope of this study it is assumed, based

---

⁶ This study uses China and India as relatable cases to represent developing countries’ demand growth, as together they are likely to account for the biggest share of global demand growth. However, there will be a host of other countries too who are likely to follow similar patterns of low-cost economic growth.
on the current political and economic rhetoric, and estimates by studies (such as BP, 2018; 2019), that some oil will continue to remain in the energy mix of almost all countries in the foreseeable future. BP forecasts that the global oil market is set to continue to expand for the next decade or so, with growing demand from developing economies met by increased supplies mainly from the US and OPEC. Other studies indicate that because of its competitive advantage given its high energy density it may be realistically unlikely to displace oil for many decades in transportation systems (Dale & Fattouh, 2018). This study uses China and India as relatable cases to represent developing countries’ demand growth, as together they are likely to account for the biggest share of global demand growth. However, there will be a host of other countries too that are likely to follow similar patterns of low-cost economic growth. Furthermore, the growth in oil consumption by India and China in response to low oil prices is a likely future possibility suggested by many oil industry analyses (BP; IEA; EIA). Such a future pathway is extremely concerning to a climate-conscious global community.

This scenario is an imaginary future scenario and reflective of a hopeful future. It is presented as SD modelling reveals a somewhat counter-intuitive consequence of the proposition. One of the valuable attributes of SD modelling is its ability to reveal system effects that, although readily understood once revealed, are not what one might have expected ab-initio. The central proposition for the following modelling is as follows. In this scenario the world is, as stated before, divided into four aggregate downstream oil consuming regions: the USA as an established major demand entre, China as a new major source of oil demand, India as a growing source of oil demand and the rest of the world (ROW). The behaviour of the USA and the ROW taken together mimics that of the OECD countries. The model is initiated at time zero in a suppressed state. Table functions are used in the model to represent the correlation between oil demand and oil price and average GDP growth rate. In case of India and China, faster economic growth rate would result in a higher demand of oil, even at higher oil prices, reflecting inelasticity of demand. The model allows the demand to be forced down in any, or all of these global regions. Ab initio it was expected that such step would reduce global oil demand significantly and indeed it does eventually, as can be seen in Figures 4.11 b in the case of a forced reduction.

The model starts at time zero in a suppressed but equilibrated level as determined by test modelling. In the case of figure 4.11, ROW demand is forced down by 90%. Such an exaggerated response to Net Zero is entirely conceivable arising from a strong political desire to mitigate climate change causing emissions. The model is allowed to run from the suppressed state (e.g. ROW 90% demand suppression) whereby the ROW demand remains held down artificially. The model clearly shows a direct price response; as prices fall, demand in the unconstrained regions rises fast. The level of that non-ROW response is remarkable. It prompts whole system oscillation such that four years in total
global demand comes close to touching levels seen without ROW demand suppression. Of course, this is simply market oscillation but the magnitude of such effects might be enormous.

The simulation results showcase that following an almost 90% reduction in oil demand by the ROW countries, the total demand at long-term equilibrium drops from 28 billion barrels per year to 20 billion. The global enduring shortfall falls short of what one might expect given the original importance of ROW countries to total demand due to dynamic response by the unconstrained territories. The modelling shown in figure 4.11 shows that the impact, and the limits to the impact, of unilateral action if only one part of the world moves aggressively in response to the threat of global climate change. Looking beyond bold action by one region one can imagine firm and enduring climate action by three of the world’s four modelled demand centres.

It must be categorically mentioned that the range of uncertainty in the likely behaviour is huge as very different paths can originate with the smallest changes in assumptions about the factors determining oil demand, such as GDP growth rate or the local political or social context, or even the rate of improvement in efficiency of vehicles, or changes in policy direction in response to building pressures to decarbonise. It can, however, be assumed that a scenario in which climate response overrides policies and countries resolve to take concrete actions to reduce carbon emissions and improve air quality, there are strong indications for a likely prospect of peak oil demand with concerted global effort to saturate and in due course reduce oil demand.

Looking beyond bold action by one region one can imagine firm and enduring climate action by three of the world’s four modelled demand centres. This is a scenario variant in which China acts to strongly (90%) suppress its demand, with somewhat weaker (60%) forced suppression in the ROW. In this scenario India remains only weakly constrained with only 10% demand reduction. Figure 4.12
shows the response of global demand in such a heavily constrained scenario. Dynamics are still clearly visible and are similar in scope and style to those seen in figure 4.11b.

![Graph showing Total Oil Demand response to China demand reduction](image)

**Figure 4.12: Total Oil Demand response to China demand reduction**

The impact of the steep demand reduction in China is significant, Figure 4.12. The simulation result shows that a similar reduction in total demand from 28 Billion barrels per year to 20 Billion as in the earlier ROW 90% scenario can be achieved. Again, powerful oscillations are seen, in this case dominated by the Indian response. Figure 4.12 reveals the established importance of Chinese demand in global oil dynamics – sufficient to shift overall equilibrated demand levels almost as much as the ROW. Together figures 4.11 and 4.12 show that the presence of any large unconstrained growth market has the power to generate whole system oscillation dynamics. Looking ahead, one can infer that India will be a territory to watch closely. The cheap-oil-induced GDP growth is likely to further inflate the demand of oil. This increased demand growth may help the oil prices to recover to some extent, and it may become profitable for some non-OPEC producers to become marginal suppliers of oil. Experts believe that the crash in prices could potentially trigger the so-called ‘rebound effect’, in which falling prices stimulate higher demand (Dale and Fattouh, 2018). The outcomes of rebound effect on China and India’s demand as a response to emerging oil dynamics are very likely to manifest very differently based on the specific policy choices in these countries. While the modelling may not capture these truths in their entirety or provide quantitative guidance on the actual magnitudes of change. Furthermore the modelling is deliberately somewhat naive in its treatment of US behaviours preferring to focus on the importance of recent arrivals China and India. What the modelling does do is suggest fundamental truths regarding the importance of various global actors and the extent to which oil market dynamics becomes a concern when thinking about climate change motivated demand side actions.
The results show that despite an almost 90 percent reduction in oil demand by all the countries, the total demand remains high if China and India maintain their oil consumption at current levels. It was also observed that even if India increased its net oil consumption by almost four-times, a decrease in China demand factor by half will be a strong enough driver for bringing the total global demand down.

**Summary:** The fundamentals of exchanges in global markets are identified. Details of oil price formation are presented. With the commoditisation of oil, the regular interactions between financial instruments of commodity markets and physical layers of oil supply-demand dynamics can be seen to determine and account for various trends and behaviour patterns observed in oil markets.

This chapter also presents a system dynamics-based analysis of the fundamental dynamics and exchanges underpinning the global oil markets. The SD model is developed to consider two sets of scenarios. The first set considers a brief but serious supply side shortfall in OPEC crude oil production. The second examines the extended effects of a global or OECD move away from oil as a fuel as might occur for climate change reasons.

In determining the **future effect of oil price points on the demand of oil**, results show a direct price response on the demand of oil in developing countries; as prices fall, demand in India and China rises fast. The modelling reveals that global oil market dynamics must consider China and India, both because China alone can shift long-term oil demand and oil prices, but also because the existence of large flexible and unconstrained players like India can drive oil market oscillations very significantly. Any policy makers contemplating the much-needed reduction in OECD oil use should pause to reflect on possible global consequences arising purely from market dynamics and without geopolitical interventions.
Chapter 5. Coal in the 21st Century: a climate of change and uncertainty

The contents of this chapter can be found in part or whole in the following peer-reviewed publications:


Context

Coal presents a particular set of challenges when balancing energy policy goals. Despite presenting viable solutions to the problems of energy security and global energy poverty, coal struggles, given its greenhouse-gas drawbacks, in a world of increasingly harmful climate change. Notwithstanding the harm caused to the environment, coal remains an expanding low-price route to meeting local energy needs. It is forecasted to remain a major global resource for the foreseeable future. In the short term it is predicted to have a 26% share of the global energy mix. Recent years have witnessed severe deviations from previously stable trends in coal markets and policy dynamics. According to the predictions by the International Energy Agency (IEA), a variety of factors ranging from the planned phase-out of coal in countries such as Denmark, France and the UK, to changes in policy in China and import-dependency in India, and demand drop in the US have together resulted in the largest decline in coal production in 2015 since 1971 (IEA, Coal Information, 2016). This chapter seeks to outline basic coal facts, recent market trends and directions globally and provides an overview of issues shaping the future of coal in the twenty-first century.

Overview

Coal has been one of the most important sources of primary energy, together with oil and natural gas, for many decades now. In 2016, despite falling demand, coal accounted for 26% of the global energy mix, at a total of 5357 Mtce (1 Mt of coal equivalent = 0.67 Mt of oil equivalent = 7.778 TWh) (IEA, 2017). While demand for coal, according to the International Energy Agency (IEA) projections, is forecast to undergo a slow and structural decline in Europe, Canada, the US and China, it is predicted to grow in India, southeast Asia and some other Asian countries (IEA, 2017).

Despite complex trends in both supply and demand, it can be stated with some confidence that coal will continue to be a significant part of the global energy mix in the mid-to-long-term. To be able to fully analyse the future of coal, it is paramount to understand factors over the past many decades that have contributed to the current status and position of coal in the energy mix.
Evidence of coal burning can be traced to the Bronze Age in Britain (Everett et al., 2012). Historically, coal was primarily used to replace burning wood for heating, cooking, lighting, and for industrial production. In the 1600s, coke replaced charcoal for smelting iron, which was later used to produce large cast-iron cylinders for steam engines. Coal made a noteworthy contribution to Britain’s performance as an industrial nation throughout the eighteenth, nineteenth and twentieth century by fuelling industrial machinery and almost all modes of transportation (Supple, 1989:5).

The development of the steam engine on the back of James Watt’s condenser invention in the 1780s, the steam turbine and the later electric generator in the nineteenth century drove economic growth increasing coal output across all industrialised nations. In Britain, coal production grew at 3.5 percent a year, from ten million tons in 1800 to over eighty million tons in 1861. The world production of coal in 1900 was estimated at 800 million tons and growing at about 5 percent annually (Everett et al., 2012: pp. 145–146). Over many decades, coal has retained its position of prominence in the energy mix owing not just to its relative ease of extraction and global abundance, but its wide range of types and associated uses.

In more recent times, resulting from a combination of factors, the otherwise stable growth trajectory of coal has witnessed serious fluctuations. These changes, resulting from shifts in global demand centres and trade flows, have, in effect, triggered significant shifts in energy geopolitics. Concerns over changing climate and seriously deteriorating air quality in many cities of the world, coupled with a rather slow transition to clean energy pathways have challenged the viability and place of coal in the future energy mix. In addition, because of its cost competitiveness, affordability and wide availability, coal emerges more prominent than ever in ensuring security of supply for fast-growing developing economies. This chapter provides an overview of coal facts, characteristic features and principles that have guided the emergence of coal over the centuries as a primary energy source. It also outlines the recent developments in market structure and policy paradigm that are likely to impact the place of coal in the future global energy mix. These fundamental realities are important considerations for designing future energy systems that can meet the wider energy policy objectives fairly and equitably for all the nations of the world. The sections that follow span consideration of the formation of coal through to its classification, uses and current reserves. The chapter outlines in some detail changes in coal demand, trading mechanisms and emerging coal futures and it concludes with a projected outlook into the future.
Coal Facts

Classification of coal

Coal was generated in the Carboniferous Period starting around 360 million to 290 million years ago through the buildup of silt and other sediments (WCA, 2017). Tectonic movements in the earth’s crust buried the carbon matter of swamps and peat bogs to great depths, exposing the materials to a change in temperature and pressure, and converting them through the process known as coalification to various kinds of coals (Gross and O’Kane, 1994; Kendall et al., 2010).

The key characteristics of coal are calorific value, moisture content, residual ash, volatility and sulfur content (which can vary greatly, depending on the area where it is mined). Coal can be classified based on its rank and its constituent microscopic organic constituents, also known as macerals.

Macerals are optically homogenous aggregates of organic substances possessing distinct chemical and physical properties, which give coal its distinct properties (Spackman, 1958; also Scott, 2002).

The classification of coal is important as it determines its best use. The British Geological Survey classifies coal as humic (composed of woody remain of plant debris) or sapropelic (containing wax-rich remains of plant spores and algae). Humic coal is further sub-classified as vitrain, clarain, durain and fusain; and sapropelic coal as cannel coal and bog head coal (Kendall et al., 2010). Based on macerals coal can be divided into the lithological types classified as vitrinite, exinite and intertinite.

The structure of coal consists of rings of six carbon atoms in layered arrangement with hydrogen, oxygen, traces of organic components like sulfur and nitrogen, together with some moisture and other inert mineral materials (for details on coal classification, see Chaudhuri, 2016; Scott, 2002). A full chemical analysis of coal to list the main constituents by mass can be done by a process called an ultimate analysis. The percentage of fixed carbon in coal is determined by a process called proximate analysis (for details see Karr, 2013).

The rank of coal is the measure of the degree of metamorphism, or coalification, undergone by it, which in turn also indicates the amount of moisture and carbon present. Based on its rank, for example, coal can be classified as hard (or black) coal or brown coal. Hard coal types like bituminous and anthracite rank higher than lignite and sub-bituminous coal. Lignite or brown coal is also often used for electricity production but its calorific value is usually much lower than that of thermal coal. Lignite is usually produced and used domestically and any international trade is negligible. This is a consequence of the unattractive ratio of transport costs to commodity value. The heat value of different types of coal is determined by its composition. The percentage of fixed carbon, hydrogen and oxygen can be analysed by proximate analysis of coal. As the rank of coal increases, so does its
Uses of Coal - Why the world needs coal?

Coal has been used to generate electricity, for key industrial processes such as steel production and cement manufacturing, and as a precursor to liquid fuels. The type of coal used for electricity generation is usually referred to as steam or thermal coal, while coal used for steel manufacturing is metallurgical coal or coking coal. The main difference between the two is in their end use based on properties such as carbon content and calorific value, with typical calorific value of steam coal at 6,000kCal/kg (these can vary based on the geographical region). A number of by-products, commonly known as coal-combustion products (CCPs) are also produced by burning coal in coal-fired power plants, these can have important industrial uses.

Steam or thermal coal is used to generate electricity in coal-fired power plants, where powdered, or pulverised coal, is blown into combustion chambers of the boilers and burnt at high temperatures. The water is converted into steam in tubes lining the boiler. The high-pressure steam rotates the blades of the turbine shaft at high speed and generates electricity. The steam passes through the
turbine and returns back to the boiler in condensed form to undergo subsequent cycles, as shown in Figure 5.2. Currently, around 40% of global electricity is generated by coal (WCA, 2017).

As the industry is currently configured, coal is dominant in the manufacture of iron and steel. Steel is the very backbone of heavy industry activities (e.g., shipping, aviation, building, utilities, equipment etc.). Around 64% of steel produced globally uses iron made from blast furnaces that are coal-fired. Iron ore, coking coal and limestone (used as flux to collect impurities) serve as raw materials, which are fed from the top of the blast furnace, while hot air (around 1200°C) is blown into the lower sections.

The hot air burns the coke to produce carbon monoxide, which removes the oxygen and reduces the iron ore to molten iron, which is drained off the furnace through taps at the bottom of the furnace. The molten iron and slag thus produced is treated with additional limestone and 99 percent pure oxygen at basic oxygen furnaces (BOF), which increases the temperature up to 1700°C. In the BOF, small amounts of steel scrap (less than 30 percent) are mixed with the iron and flux. The scrap melts at these high temperatures, oxidises the impurities, and reduces the carbon content by 90 percent. The process results in the production of liquid steel as shown in Figure 5.3.

---

**Figure 5.2: Electricity Generation using Coal**

*Source: Adapted from World Coal Association (https://www.worldcoal.org/coal/uses-coal/coal-electricity)*
Around 64% of world steel today is produced at BOFs, while 33% are produced at electric arc furnaces (ERF). At ERF, electrodes are subjected to power to produce an arc of electricity, which in turn raises the temperature to 1600°C to produce molten steel. Pulverised coal injection (PCI) technology allows a wide variety of coal, including relatively cheaper steam coal, to be injected directly into the blast furnace and is increasingly being used, as reported by the World Coal Association (WCA, 2017).

Coal is also used as a liquid fuel, which can be further refined through a process called liquefaction to produce transport fuels and other oil-generated products like plastics and solvents. There are two different approaches to liquefaction: direct and indirect liquefaction. Direct coal liquefaction (DCL) technology involves converting coal to partially refined synthetic crude oil, which can be further refined to produce synthetic gasoline, diesel and other hydrocarbon products similar to those derived from crude oil. In indirect coal liquefaction (ICL) coal is gasified to make synthesis gas or ‘syngas’, which can be then used to produce synthetic oil products (Williams and Larson, 2003: 103-104). (Further details on liquefaction can be found in Williams and Larson, 2003).

By acting as a substitute for crude oil in a world scrambling for secure supplies of energy, coal further increases its presence in the energy mix. Based on the Fischer–Tropsch process, the largest
coal-to-liquid (CTL) production capacity is currently located in South Africa (Energy Information Administration, 2010). This coal-based commercial liquefaction process has been estimated to meet one-third of the current domestic liquid fuel requirement in South Africa (WCI, 2005a, 2005b). Figure 5.4 shows some of the liquid fuel products produced by coal gasification (WCI, 2007).

![Figure 5.4: Coal Liquid and Gaseous Fuel Products](Source: Inspired by World Coal Institute, 2006)

Coal is also used as an energy source to produce cement. High-temperature kilns burn coal in powdered form, which raises the temperature to 1450°C, altering the physical and chemical properties of calcium carbonate, silica, iron oxide and alumina and produces clinker, which is mixed with gypsum and finely ground to produce cement. Important CCPs include fly ash, bottom ash, boiler slag and flue gas desulfurisation gypsum, most of which can be recycled and used as important replacements for primary raw materials (WCI, 2005a, 2005b).
Box 5.1: Coal to Gas

In around 1800, coal was burned in the absence of air, producing an illuminating gas, which was used for commercial gas lighting. This gas contained sulphur impurities of coal, present as hydrogen sulphide, and nitrogen in the form of ammonia. This noxious gas was later piped into homes and even used as a controllable fuel source for cooking. Most towns and cities in the industrialised countries, by the end of nineteenth century, had a gasworks that produced 'town gas' and coke (Thomas, 2014).

The process of producing combustible town gas from coal was as follows: bituminous coal was loaded into closed retorts and heated at very high temperatures. The impure gas that was produced was then cleaned through a set of processes which included bubbling it through water to dissolve the ammonia produced by coal’s nitrogen and dissolving the oil and tars as a liquid layer; passing the gas over iron oxide to remove hydrogen sulphide; and putting the gas through a final wash to remove any remaining impurities like benzene. The final cleaned gas contained carbon monoxide, methane hydrogen and hydrocarbons like ethylene and acetylene. The bright illuminating colour of the gas came from its hydrocarbon components. The residual material would be a batch of coke, which could be reused in coal furnaces or sold as a heating fuel. A range of other end products, with important applications, could also be recovered. The ammonia was sold as fertiliser, coal tar was distilled into a range of oils: light (boiling point (bp) <200°C), middle (bp 200-240°C), heavy (bp 240-270°C) or anthracene (bp 270-360°C), and the residual thick tar and pitch was even used for making roads. Other ways to make gas from coal were also employed at this time, one of which was by spraying water on red-hot coke making what was known as ‘water gas’ (Ramage et al., 2012; Shadle et al.; 2000 Thomas, 2014).

The basic distillation process improved over time, producing more gas and making it cheaper. By the 1920s town gas was sold in similar manner to how natural gas is today-metered and based on heat content. Natural gas today has completely replaced town gas, because of its higher energy density, better cleanliness and greatly reduced toxicity. Nevertheless, one must acknowledge that town gas did greatly modernize heating, cooking and lighting in the nineteenth century.
International Coal Markets and Trade: a shift to the East

The last two decades have been remarkable for the coal sector. The global structure and trends of coal demand have gone through a series of significant changes primarily with the emergence of demand growth from economies in the east and growing concerns over environmental protection. Historically, coal markets have been highly localised and specific to specialised markets. The emergence of seaborne trade for coal has indeed unified these separate coal markets into a functional market that traded 1333.5 Mt of coal, representing 17.6% of coal consumption on an energy basis in 2016 (IEA, 2017). The following sections highlight some of the defining features of coal markets and international trading of coal.

Global Coal Markets

Two different kinds of markets exist for internationally traded coal: the steam coal market for power generation, and the coking coal market for its use as a chemical reductant as well as an energy source. There are also maritime and inland markets for coal, but the inland trade is relatively negligible in comparison and only takes place between neighbouring countries. In this chapter, as in most other publications, the focus remains on the maritime trade of coal, because of its wider policy and market implications. The maritime hard coal market can be further broken down into steam and coking coal markets. It must also be stated that the markets for coking and steam coal are not always distinct, although the market for coking coal is more unified and unitary with a few suppliers serving the market (Ritschel & Schiffer, 2007). The seaborne thermal or steam coal market comprises two segments: the Atlantic Market (comprising North, Central and South America, Europe and the Mediterranean countries) and the Pacific Market (serving Asian consumers). Distances determine the mode of coal transportation, which is generally carried out over longer distances using ships, or using trucks, trains and barges over shorter distances and within domestic markets (World Coal Institute, 2005). Figure 5.5 showcases how coal is transported between various global markets.
A key factor that regulates the trade of coal is the level of freight rates, enabling Atlantic or Pacific producers to supply coal at competitive prices into distant markets (World Coal Association; Ritschel & Schiffer, 2007). The transportation cost therefore accounts for a large share of the total delivered price of coal, significantly impacting the demand and supply dynamics of sea-borne coal. Freight rates can be volatile and change very rapidly based on market conditions, reflecting broader macroeconomic drivers and conditions of other commodity markets (as goods like grain and iron ore are transported on the same vessels, together with coal). Between 2003 and 2008, freight rates rose steadily due to a variety of factors such as the increase in the coal trade, the rising demand for dry bulk carriers for transporting other commodities, the surging demand in China and strong grain exports. They reached an all-time high as commodity prices peaked in 2008 before declining by 94 percent as the world markets crashed. The leading index for dry bulk carrier rates is the Baltic Dry Index (BDI), issued by the Baltic Index (Energy Charter Secretariat, 2010). More recently, due to depressed demands of iron ore and coal and a glut of carriers, the BDI dropped to 290 points, its lowest in February 2017, on the Baltic Exchange. Fluctuating oil prices significantly impact bunker fuel costs, and in turn add volatility to the freight costs.
International Coal Trade

Through the various modes of transportation, see Figure 5.5, coal is traded all over the world. It is produced in over 50 countries and consumed in more than 70 countries. Efficient means of transportation and a large number of suppliers of coal ensures an effective global trade of coal through the formation of an emerging competitive market. According to IEA statistics, around 1333.5 Mt of coal was traded internationally in 2016. Table 5.1 presents the data on global coal trade in 2016 as reported by the IEA 2017. Steam coal exports increased by 14.6 Mt (1.5 percent) and coking coal exports by 10.2 Mt (3.4 percent). The total exports have increased by 21.7 percent between 2010 and 2016 and doubled (105.3 percent) since 2000. These figures portray well the dynamics of the global coal trade. Almost 92 percent of traded volume is seaborne, while the remainder is cross-border overland trade.
Table 5.1: World Coal Trade 2016

<table>
<thead>
<tr>
<th>Coal Trade</th>
<th>Amount of coal traded in megatonnes (Mt) of coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Coal Exports</td>
<td>1010.4</td>
</tr>
<tr>
<td>Coking Coal Exports</td>
<td>314.1</td>
</tr>
<tr>
<td>Lignite exports</td>
<td>9.0</td>
</tr>
<tr>
<td>Steam Coal Imports</td>
<td>1045.0</td>
</tr>
<tr>
<td>Coking Coal Imports</td>
<td>282.1</td>
</tr>
<tr>
<td>Lignite Imports</td>
<td>402</td>
</tr>
<tr>
<td>Total Exports</td>
<td>1333.5</td>
</tr>
<tr>
<td>Total Imports</td>
<td>1331.3</td>
</tr>
<tr>
<td>Balancing Item*</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

*Balancing Item is the difference between total coal imports and exports, and takes into account coal in-transit, unaccounted for coal, and various reporting discrepancies followed by importing and exporting countries.


Australia and Indonesia remained the largest coal exporters in 2016 accounting for 29.2 percent and 27.7 percent of the total quantity exported, while the Russian Federation contributed to a 12.8 percent share of the total. The ten largest exporting countries, which also included Colombia (6.2 percent), South Africa (5.7 percent), United States (4.1 percent), Netherlands (3 percent), Canada (2.2 percent), Mongolia (1.9 percent) and Kazakhstan (1.9 percent). Together these 10 countries shipped 95 percent of global coal exports. A total of 1331.3 Mt of coal was imported in 2016, according to IEA reports, of which The People’s Republic of China imported 19.2 percent and India 15 percent. Other top importers included Japan, Korea, Chinese Taipei, Netherlands, Germany, Turkey, Malaysia and the Russian Federation. A global overview of coal trade that took place between various markets in 2014 is showcased in Figure 5.7. It is not surprising that the biggest importers are China and India, the countries with the largest populations in the world. They are also two of the fastest growing large economies under huge economic and political pressures to make electricity available to their expanding population and industrial bases.
A number of factors contribute to the changing dynamics and rapid development in the global coal trade. All key forecasts assume ongoing growth in coal consumption and world trade backed by a strong growth and changing policy dynamics in developing countries like India, China and Southeast Asian countries. While there is strong growth in the Asian region, a steady decline is predicted in European production and consumption. Another important factor is the relative cost competitiveness of world, or traded, coal over domestic coal and the ease with which coal can be shipped across markets with falling freight rates. This has significantly changed the global trade dynamics of coal. Additionally, the emergence of new swing suppliers has also significantly impacted the coal trade dynamics.

Historically, geography has been a major component shaping coal trade markets with set boundaries and well-established suppliers within each market. The United States and subsequently South Africa were the major established marginal or ‘swing’ suppliers of coal to both the Atlantic and Pacific markets (Cameron, 1997). In his pioneering work, The World Price of Coal, Ellerman bases his findings on the principle that ‘US is the residual supplier of coal, determining the upper limit to prices in the world coal market’ (Ellerman, 1999: 499; also Cameron, 1997: 24). In the 1980s, US had a large domestic market and substantial railroad and port capacity to bolster its place as the residual supplier (Light et al., 1999). South Africa’s pattern of export, on the other hand, changed as a response to economic sanctions imposed on it from July 1986 to 1992/3. Its exports to Asia during
this period more than doubled, but subsequently declined (Cameron, 1997). The global trade landscape of the 2000s is very different from what it was in the late 1980s and 1990s. Many swing suppliers, i.e. those that supply coal depending on attractive price and market situations, are now routinely trading into both markets, backed by massive reductions in freight costs in recent years. Figure 5.8 highlights the coal movements in 2015.

**Figure 5.8: Coal movements in the Pacific Market in 2015 (Mt)**


**International Coal pricing**

Coal markets are rapidly evolving into commodity trading markets and transactions based on coal indices are becoming established. Not long ago the spot markets for coal were not clearly defined (Cameron, 1997). However, with the emergence of coal futures and derivatives, and the establishment of global coal exchanges, the market structure for coal has changed significantly (Energy Charter Secretariat, 2010).

**Recent price developments**

The prices of internationally traded coal are commonly expressed in US dollars per ton or ton coal equivalent (tce). As shown in Figure 5.8 coal exports use FOB (free on board) prices- the price of coal and the cost incurred to transport coal from the mine to a terminal in the country exporting it. Imports use CIF (cost, insurance and freight) prices- the FOB price plus the cost to transport coal to the receiving port in the importing country. Free at Shipside (FAS) price, which does not include the
cost of loading, is used in the US instead of the FOB price (Energy Charter Secretariat, 2007). Prices for coal vary according to its uses, attributes and markets. Historically, coking coal prices were higher than those for thermal or steam coal prices. Growing electricity needs for increasing populations in emerging economies, however, have rapidly expanded the international trade in thermal coal.

![Coal Prices Diagram]

Representative cost of coal supply chain includes free mine costs, domestic transport costs, port-handling costs, sea freight cost etc.

**Figure 5.9: Development of coal prices**


The cost of various constituent stages of the coal supply chain are crucial in determining its cost competitiveness over other sources of primary energy. For example, coal is less capital intensive than oil and gas, requiring comparatively less investment in developing new mining capacities and carrying significantly less investment risks than the latter. This becomes evident in the order presented for each energy source based on the total investments needed during the entire supply chain (expressed in tons of coal equivalent, tce): Coal- USD 3.4/tce; Oil- USD 15.4/tce; Gas- USD 19.6/tce, as identified by The World Energy Investment Outlook of the IEA (Ritschel & Schiffer, 2007). Other crucial components that determine the cost of coal are additional key representative costs in the value chain like free mine costs based on type of mining operation (whether it be opencast or underground mine), domestic transport cost, port handling cost, sea freight costs, labour and productivity cost, etc., as shown in Figure 5.9. These costs differ across a range of attributing factors which are specific to the countries where the coal comes from and sells into, explaining the large cost range of coal. Freight rates account significantly towards final cost of traded coal and thus have a direct impact on its demand and trade flows. More details on the Baltic Dry Index have been presented in Box 5.2.

The recent price competition in the world’s coal markets has been mostly governed by fluctuating supply and demand cycles, with shortages in supply following excessive supply resulting from steadily rising capacity utilisation of the mining capacities for exports. This triggered volatilities and
price peaks. Competitive CIF prices make it profitable for suppliers to trade coal between markets. Depending on the price situation, coal varieties are interchangeably used with certain steam coals prepared and marketed as more volatile coking coals and vice versa.

**Coal contracts**

Long-term contracts are very widely used in the coal sector because of associated capital investments and characteristic quality mediated usage and are formed between coal buyers and sellers. These serve as an important indication into future developments, impacting decisions on long-term investments. The pricing system, under long-term contracts, has undergone systemic structural changes in the past decades. Traditionally, Benchmark Prices were based on FOB prices. However, in more recent times short-term and spot contracts exist alongside these long-term contracts (Energy Charter Secretariat, 2010). Some of the notable players in the international coal market are listed in Table 5.2.

### Table 5.2: Global Market Players in Coal Trade

<table>
<thead>
<tr>
<th>Electronic Trading Platforms</th>
<th>Banks</th>
<th>Physical Coal Trading Companies</th>
<th>Utility Traders of Physical Coal</th>
<th>Bank Traders of Physical Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GlobalCOAL</td>
<td>• Morgan Stanley, Merrill Lynch, Macquarie Bank</td>
<td>• GLENCORE</td>
<td>• EDF TRADING</td>
<td>• Macquarie Group</td>
</tr>
<tr>
<td>• Glencore</td>
<td>• RBS Sempra</td>
<td>• CARRIL</td>
<td>• RWE Supply &amp; Trading</td>
<td>• RBS Sempra Energy</td>
</tr>
<tr>
<td></td>
<td>• EDF Trading</td>
<td>• NOBLE GROUP</td>
<td>• NUON</td>
<td>• Goldman Sachs</td>
</tr>
<tr>
<td></td>
<td>• E.ON Trading</td>
<td>• VITOL GROUP</td>
<td>• Essent</td>
<td>• Morgan Stanley</td>
</tr>
<tr>
<td></td>
<td>• RWE</td>
<td>• TRAFIGURA</td>
<td></td>
<td>• Merrill Lynch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• MERCURIA ENERGY GROUP LTD</td>
<td></td>
<td>• Deutsche Bank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• LOUIS DREYFUS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• HIGHLRIDGE ENERGY LLC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BULK TRADING SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• FLAME SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PEABODY ENERGY</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


**Coal Spot Prices, Futures and Derivatives**

Both long-term supply contracts and spot contracts exist between sellers and buyers in the world hard coal markets. Spot contracts help the consumers establish closer alignments with the existing market situations, while long-term contracts are mostly encountered in cases where enduring interdependencies exist between producers and consumers. Tender deals, or purchases, linked to bidding procedure is a common variant of spot purchases for deliveries involving larger volumes and covering longer time-scales. Spot transactions have important features making them an important instrument in the coal price formation mechanism. Spot prices allow for mark-ups to be levied on long-term contract prices in tight market conditions, and for price reductions when market conditions become relaxed. Spot prices in buyers’ markets therefore remain below longer-term
contract prices. Spot prices also perform a marker function for contracts for future deliveries, thereby affecting their prices (Ritschel and Schiffer, 2007).

A number of well-established spot prices exit at different locations. Two important spot prices for coal exports are: FOB spot price at Richards Bay, South Africa and FOB spot price at Newcastle, Australia. The main import prices are CIF spot prices at Amsterdam-Rotterdam-Antwerp (ARA) in Northwest Europe and Japanese import CIF prices. A number of regional spot prices such as the ‘Central Appalachia’, ‘Northern Appalachia’, ‘Illinois Basin’, ‘Powder River Basin’ and ‘Uinta Basin’ exist in the US. These spot prices are regularly published by reporting agencies e.g. Argus, McCloskey Coal Information Services (MCIS), Platts and South African Coal Report (SACR) (Energy Charter Secretariat, 2010).

Coal trading, with the development of electronic trading and financial derivatives, has undergone a step transition in the recent past and can be considered representative of future markets. Coal is now traded financially on paper or physically, by, and among, new participating players like banks and financial institutions, as well as existing ones like electricity utilities and mining companies changing the traditional nature of coal trading and pricing. Coal futures markets are less mature than oil futures markets at this stage, as coal futures contracts still tend to be settled in cash against published indices, except at the New York Mercantile Exchange (NYMEX) and the ASX (Australian Securities Exchange).

Before the onset of futures markets, over-the-counter (OTC) swap markets were the popular trading instrument. OTC trading took place outside the exchange in the form of a negotiation between two parties and thus differed from a futures or derivatives exchange - a financial institution overseeing a standardised exchange of contract between involved parties (Energy Charter Secretariat, 2010). A swap helps hedge against price risks by enabling the player to exchange the price of a chosen brand with a fixed price, or a benchmark linked price, or that linked to a composite index for a specified amount of time by entering into an arrangement with a financial institution. The terms of an OTC derivative can be customised to suit the parties involved in the negotiation, and can be very opaque by virtue of these being less regulated.

All Publications Index number 2(API2), a price index of CIF steam coal delivered to the ARA (Amsterdam-Rotterdam-Antwerp) area in Northwest Europe, is the largest coal derivatives market, followed by API4, a price index of FOB steam coal at Richard’s Bay. API2 and API4 are respectively the arithmetic mean of the CIF and FOB assessment published by specific reporting agencies from specified locations in named journals. Global Coal, headquartered in London, is an electronic platform that was created in 2001 by coal producers, end-users and others. Trading activities at the
Global Coal electronic platform are compiled and published as the Newcastle (NEWC) Price Index, which is based on FOB steam coal prices at the NEWC terminal in Australia. It is an established benchmark for the Asia-Pacific steam coal market. NYMEX started trading coal futures in 2001 seeking to provide both the buyers as well as sellers with tools to hedge risks against price volatility. A number of other coal futures markets such as London’s Intercontinental Exchange (ICE) and Global Coal, Germany’s European Energy Exchange (EEX) and Australian Securities Exchange (ASX) have since been established. ICE Rotterdam futures and EEX ARA futures are settled against the API2 index in cash, while the ICE Richards Bay futures and EEX’s ICE Richard’s Bay futures are settled similarly against the API4 index. While Global Coal’s NEWC futures is settled against NEWC index in cash, ASX’s FOB Newcastle futures are settled by physical delivery (Energy Charter Secretariat, 2010). A list of some of the coal price indices are given in Table 5.3.

**Table 5.3: Various Coal Price Indices**

<table>
<thead>
<tr>
<th>Index Description</th>
<th>Index Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW Europe CIF (6,000kc NAR)</td>
<td>Part of API 2</td>
</tr>
<tr>
<td>Richards Bay FOB (6,000kc NAR)</td>
<td>Part of API 4</td>
</tr>
<tr>
<td>South African FOB (5,500kc NAR)</td>
<td>Part of API 3</td>
</tr>
<tr>
<td>Australian FOB (5,500kc NAR)</td>
<td>Part of API 5</td>
</tr>
<tr>
<td>Newcastle FOB (6,000kc NAR)</td>
<td>Part of API 6</td>
</tr>
<tr>
<td>South China CFR (5,500kc NAR)</td>
<td>Part of API 8</td>
</tr>
<tr>
<td>South China CFR (4,900kc, 6,000kc NAR)</td>
<td>Produced with Xinhua</td>
</tr>
<tr>
<td>Qinhuangdao (domestic/export FOB)</td>
<td>(5,000, 5,800, 6,000kc)</td>
</tr>
<tr>
<td>Indonesian FOB (6,000kc NAR) / FOB (5,500kc NAR)</td>
<td></td>
</tr>
<tr>
<td>Indonesian Sub-Bit FOB 4,900kc NAR, 4,200kc/3,800kc GAR</td>
<td></td>
</tr>
<tr>
<td>Indian CFR (5,500kc NAR) East &amp; West coast</td>
<td>Part of API 12</td>
</tr>
<tr>
<td>India East Coast CFR &amp; West Coast (5,000kc / 4,200kc)</td>
<td></td>
</tr>
<tr>
<td>US East Coast &amp; US Gulf High Sulphur FOB (6,000kc)</td>
<td></td>
</tr>
<tr>
<td>Bolivar Colombian FOB (6,000kc NAR)</td>
<td>Part of API 10</td>
</tr>
<tr>
<td>Russian West Coast FOB (6,000kc NAR) East Coast (6,700kc)</td>
<td></td>
</tr>
<tr>
<td>NEX (Newcastle Thermal Coal Export) Index</td>
<td></td>
</tr>
</tbody>
</table>


Price competition in commodities markets is typically governed by supply and demand for most commodities. However, in the case of coal, factors that can potentially impact demand and supply dynamics such as the recent move to decarbonise energy pathways, or fluctuations in the cost of crude oil can also cause price movements, albeit indirectly. Different pricing mechanisms are also followed in Pacific and Atlantic markets. In cases of competitive CIF prices, inter-market deliveries become cost efficient. Distant suppliers become more competitive when the freight costs are lower. Any extra transport cost is normally borne by the suppliers. Today’s coal market leaders must consider all the prices offered by various competitors to retain market share, as coal is traded on a spot basis. The CIF prices at the destination port are important for any price-level formation, which in turn, serves as the benchmark for long-term price negotiations. Carbon dioxide certificate trading may also in effect add to the price of coal when comparing the cost of other competing sources of energy and will be an important consideration in future. Long-term as well as spot transactions are now a common market phenomenon (Ritschel and Schiffer, 2007).
Coal markets internationally are very dynamic, comprising of a large number of suppliers actively supporting the power and manufacturing needs of countries, trading across markets, through a variety of quantities and instruments across a range of price indices for different regions. Despite these market dynamics, changes in demand for coal across various regions have resulted in severe volatility in coal prices over the past decade. However, the development of coal futures and derivatives is an indication that market mechanisms will significantly determine the future of coal. Figure 5.10 showcases the volatility in various coal price between 2000 and 2016 as reported by the BP Statistical Review.

Coal’s otherwise stable growth trajectory has witnessed drastic changes in the past two decades fuelled by rapid growth after 2000 and a subsequent slow-down in 2014-15 in the developing economies. With a growth in demand, coal prices rose sharply as buyers purchased excessive amounts to counter any disruption in supply. The state of demand increased coal prices between 2003 and 2004, with some stabilisation in 2005. This was followed by yet another sharp increase in 2008 followed by a drastic decline in the wake of the global economic downturn of that time. Several reforms have been introduced by countries towards making coal prices (particularly domestic prices) more market-based (e.g. deregulation of coal prices in India and market-based pricing for coking coal in China) (ICS 2010). However, despite this, coal prices have remained extremely volatile due to a combination of factors including a new political regime in the United States with the election of President Trump, and capacity expansion in Southeast Asian countries. According to the IEA, coal prices are predicted to remain volatile and are likely to be affected heavily by economic rebalancing in policy priorities in major demand centres like China, India, Korea and Japan (International Energy Agency, 2017).
Coal and Climate Change

Scientists have reported that the concentration of carbon dioxide (CO$_2$) in the atmosphere was about 40 percent higher in 2016 than in the mid-1800s, with the energy sector representing the largest share of global anthropogenic greenhouse gas (GHG) emissions—approximately 68 percent (IPCC, 2013). The growing concerns over rapid climate change resulting from anthropogenic GHG emissions have shaped much of the public and political debate for a little over twenty-five years. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) committed parties to an international treaty to combat climate change with the goal of limiting global average temperature increases putting in place a range of adaptation and mitigation strategies. Although no binding GHG emission reduction commitments were set on any individual country at the time. These parties have met annually since 1995 at the Conference of Parties (COP) to evaluate the progress of efforts in dealing with climate change. Several milestones in climate negotiation have since been passed such as the Kyoto Protocol in 1997, the Copenhagen Accord of 2009 and more recently the 2015 Paris Agreement, which marks the latest step in the evolution of climate change and energy
policies across the world (UNFCCC, 2016). These agreements are influential in maintaining significant pressure on the polluting fossil-fuels sector, and seek to significantly alter the existing energy systems towards cleaner, more efficient and sustainable activity.

Within the energy sector, fossil fuel combustion dominates the total GHG emissions, of which 44 percent stems from coal (Schernikau, 2016; 45 percent as per International Energy Agency). Ecologically coal is one of the most polluting fuels, its combustion generates large amounts of CO$_2$, oxides of sulphur and nitrogen (SOx and NOx), particulate matter such as fly ash and dust, and trace elements such as mercury (Aslanian, 1991; World Coal Institute, 2005: pp29). The continued use of coal at scale via the approach in use today is therefore regarded as a major threat to the future climate.

In recognition of the need to reducing GHG emissions, substantial funding has been allocated by governments all across the globe for research, development and adoption of a wide range of technologies reducing coal-generated-emissions and bringing improved energy efficiency. Clean coal technologies aim to improve the environmental performance of coal and address a cascading set of environmental challenges. The goal is to eliminate the emission of particulate matter and other pollutants such as the oxides of sulphur and nitrogen and reducing CO$_2$ emissions per unit of electricity generated by increasing thermal efficiency (World Coal Institute).

While the IEA, on the basis of technology type, identifies five groups of clean coal technologies: coal upgrading, efficiency improvements at existing power plants, advanced technologies, near-zero emission technologies and CO$_2$ transport and storage technologies (International Energy Agency, 2009), the World Coal Institute categorises them into coal preparation, technologies for reducing emissions of pollutants, efficient combustion technologies and carbon capture utilisation and storage technologies (World Coal Institute, 2005). Table 5.4 presents an overview of some of the clean coal technology options and their current status. The Global CCS Institute reports 43 large-scale CCS projects – 18 in commercial operation, 5 under construction and 20 in various stages of development (Global CCS Institute, 2018). (More detailed information on a range of CCS projects is available at Global CCS Institute Online; also Northam et. al., 2016; IEA, 2009).

In 2015, the top anthropogenic CO$_2$ emitters were China (26 percent) -emitting primarily from coal; the US (16 percent) emitting from oil, gas and coal; India (6 percent) emitting primarily from coal; Russia (5 percent) emitting primarily from gas and Japan (4 percent) from oil, coal and gas (Schernikau, 2016). Today we do indeed see a trend away from the use of coal in some, but by no means all, wealthy developed countries (IEA, 2016; BP Statistical Review, 2016). Developing countries, on the other hand have registered a huge increase in their use of coal for electricity
generation over the past 25 years. It is worth highlighting that Asia houses 60 percent of the global population, half of which lives in China and India, the two most populous countries of the world (Baruya, 2016). While China is working towards developing lower-emission coal-fired power plants, in addition to developing other cleaner sources of energy, other developing countries in Asia continue to rely heavily on cheaper and traditional coal-fired power generation. Even if one were to be optimistic and pointed to evidence of the patchy emergence of reduced interest in the use of coal for electricity generation, it is important to recognise the major role played by coal in steel making and other heavy industrial processes (Katzer et al., 2007, see earlier sections for details on industrial uses of coal). In such areas the impact of climate concerns on coal usage would thus far appear to be even weaker than in the electricity sector. Furthermore, with a predicted increase in population and a strong desire for improvements in living standards in the emerging economies, the emissions from many developing countries are set to increase significantly. For example, coal use in India and ASEAN countries in the near future, according to various reports, including IEA's Coal 2017, is predicted to grow significantly.

Noting that in some territories a continued role of coal appears to be inevitable, and noting the need to reduce environmental harm it seems prudent to advance research and development in clean coal technologies in the short to medium term. A wider adoption and at-scale integration of clean coal technologies presents the prospect of a global clean coal technology market, which was valued at US$ 5970 million in 2017 and is predicted to grow at CAGR of 2.1 percent during 2018-2025 reaching US$ 7050 million by the end of 2025 (QYResearch Group, 2018).

With the deemed role played by coal as a contributor to the climate problem since the early 1990s, exacerbated by a nearly two-and-half-fold increase in global population and related pollution issues over the preceding three decades, disappointment must be expressed over the slow pace in which steps have been taken to reduce the output of harmful gases from the use of coal and other fossil fuels for power generation. There is hope that the anticipated future global coal utilisation might be accompanied by improved efficiency through pre-treatment and emissions clean-up, including carbon dioxide. As things stand, however, we remain some way from a low emissions future for coal and this must be seen as a major problem requiring effort over the next decade and beyond.
**Table 5.4: An Overview of “Clean Coal” Technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal Preparation</strong></td>
<td>The process includes treatment of run-of-mine (ROM) coal (coal straight from ground) to ensure an improved quality suited to its specific end-uses. The process may include washing, crushing and separating into various size fractions using tank or froth flotation. The process increases the heating value and quality of coal, and the overall efficiency of coal-fired power plants.</td>
<td>Widely developed and used both in developed and developing countries. Can be used to bring about up to 5% reduction in CO₂ emissions.</td>
</tr>
<tr>
<td><strong>Particulate Emission and Pollutant reduction technologies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activated Carbon Injection (ACI)</td>
<td>Powdered activated carbon is injected from a storage silo into the flue gas ductwork of a cement kiln or coal-fired power plant. Pollutants like mercury are absorbed on particulate matter before being removed in particulate control equipment.</td>
<td>ACI for coal-fired power plants was first tested and introduced in the early 1990s. With wider adoption of regulations like the large combustion plant best available techniques reference document (LCP BREF) and stricter limits for particulate emission, ACI technologies are likely to be widely adopted in the EU, China, India, South Africa and other coal-burning countries.</td>
</tr>
<tr>
<td>Electrostatic Precipitators (ESPs) &amp; Fabric Filters</td>
<td>ESPs and fabric filters can be used to control particulates from coal combustion. ESPs use electric filed to create a charge between collecting plates, whereas tightly woven fabric similar to a sieve is used in fabric filters to collect particles from the flue gas.</td>
<td>With a potential to remove over 99.5% of particulate emissions, these are widely used in developed as well as developing countries to improve the environmental performance of coal-fired power stations.</td>
</tr>
<tr>
<td>Hot Gas Filtration Systems</td>
<td>These operate at high temperatures (500-1000°C) and pressures (1-2 MPa).</td>
<td>Technologies such as cyclones, ceramic barrier filters, high-temperature fabric filters, granular bed filters etc. are being developed and carefully considered for enhanced commercial application.</td>
</tr>
<tr>
<td>Flue Gas Desulphurisation (FGD)</td>
<td>Sulphur emission from coal’s combustion can be removed by FGD technologies. The FGD technologies can be classified as: wet scrubbers; spray dry scrubbers; sorbent injection processes; dry scrubbers; regenerable scrubbers and combined SOₓ/NOₓ removal processes. An alkaline sorbent slurry like lime or limestone reacts with SO₂ in the flue gases forming gypsum in flue gas cleaning plant or scrubbing vessel.</td>
<td>With proven removal efficiency of 90-99%, wet particle scrubbers are used additionally to capture fly ash. This technology is widely used in the US.</td>
</tr>
<tr>
<td>Selective Catalytic Reduction (SCR) &amp; Selective Non-Catalytic Reduction (SNCR)</td>
<td>These technologies can be used to treat emissions of oxides of nitrogen (NOₓ) from coal combustion in the exhaust gas stream and have been proven to reduce NOx emissions by around 80-90%. SCR systems use ammonia vapour as a reducing agent, which is injected over the stream of flue gas and passed over a catalyst. SCR systems operate between 300°C</td>
<td></td>
</tr>
</tbody>
</table>
and 400°C, much lower than those of 870-1200°C, used by SNCR systems, thereby requiring a catalyst to speed up the chemical reactions.

### Efficient Combustion and Reducing Carbon Dioxide Emissions Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulverised Coal Combustion (PCC)</td>
<td>In power stations using PCC, coal is first pulverised and blown at high temperatures for combustion in furnaces producing steam which is used to drive turbines and generator.</td>
<td>Improvements in thermal efficiency of coal-fired power stations significantly increase the energy being produced from the fuel. Currently, the global average thermal efficiency of coal-fired power stations is around 30%, with OECD countries average ranking higher than those in developing countries. However, with new supercritical and ultra-supercritical technologies can achieve efficiency levels between 43-50%. IGCC systems can operate at close to 50% efficiency, while simultaneously removing 95-99% of NOx and SOx emissions. World Resource Institute reports around 400 supercritical plants and 160 IGCC plants operating across the world.</td>
</tr>
<tr>
<td>Fluidised Bed Combustion (FBC)</td>
<td>In FBC, gas is fed through a bed in the reactor where coal is burned, improving its combustion, heat transfer and aiding the recovery of waste products. FBC reactors operate at lower temperature than the PCC systems due to improved heat exchanges efficiencies and better mixing in FBC systems. The gas streams can be subjected to high pressures within the bed, and used to drive gas turbines producing electricity. Several kinds of FBC technologies like bubbling fluidised bed combustion, circulating fluidised bed combustion, pressurised fluidised bed combustion, pressurised circulating fluidised bed combustion exist and are being further developed.</td>
<td></td>
</tr>
<tr>
<td>Pressurised Pulverised Coal Cycle (PPCC)</td>
<td>In PPCC technologies combustion of finely pulverised cloud of coal generates high temperature and high-pressure steam, which is used in turbine generators to produce electricity.</td>
<td></td>
</tr>
<tr>
<td>Integrated Gasification Combined Cycle (IGCC)</td>
<td>In IGCC systems, coal is reacted with oxygen and steam to produce syngas (see section 2.2 for more information), which in turn is burnt in a gas turbine to generate electricity and produce steam for steam power cycle.</td>
<td></td>
</tr>
<tr>
<td>Supercritical and Ultra-supercritical Technology</td>
<td>These operate at higher steam temperature and pressures than conventional plants. At such high temperature and pressures, the single-phase fluid is passed through boilers and used in supercritical cycles, bringing about increased efficiencies of over 50%.</td>
<td></td>
</tr>
<tr>
<td>Carbon Capture Utilisation and Storage (CCUS)</td>
<td>CCUS technologies include methods and technologies to remove CO2 from the flue gas and recycling and utilising it the most efficient and safe way possible. Sorbents that can bind with the CO2 in the flue gas are used to capture carbon. The captured CO2 is then used in food processing or chemical industry, or for oil extraction or remediation of alkaline industrial wastes. However, given the limited demand of CO2 various viable storage options for CO2 are being developed. Some of the proposed options include injecting CO2 in geologic formations and oceans, and growing trees to enable biological fixation of CO2 via photosynthesis.</td>
<td>A number of CCUS projects are being test run around the world. There is significant effort underway in the UK through the government’s Clean Growth Strategy to support the development of CCUS in the UK and internationally. However, CCUS technologies are currently expensive and cost reductions are needed for any further successful deployment and its adoption in developing countries.</td>
</tr>
</tbody>
</table>

(Source: World Coal Institute; International Energy Agency, 2008; Northam et al., 2016)
Coal in the Energy Mix and Outlook 2022

The importance of coal in the energy mix can be assessed simply by the fact that about one third of all energy and 40% of the electricity generation globally is based on coal (IEA, 2017). Coal is also crucial to heavy industries like steel and iron. Of the total electricity access provided in the last two decades, around 45% was powered by coal (WCA, 2017). IEA (2017) predicts the share of coal in the energy mix in 2022 to remain at 26%, dropping 1% from 2017 levels. With reference to Figure 5.11, world proven coal reserves in 2016 were estimated at 1 139 331 Mt, sufficient to meet 153 years of global production (compared to 61 years for gas and 54 years for oil), according to BP Statistical Review (BPSRWE, 2016). Despite certain advancements in renewable capacity and falling renewable prices, coal remains competitive for electricity generation in India, China and Southeast Asia. The electricity produced from coal in these countries costs significantly less than that from most renewable sources, and will continue to play a key position in the global energy mix, looking ahead (WCA, 2013).

Figure 5.11: Total Proven Reserves vs. Consumption in 2016 (Mt)

On the whole, according to the IEA predictions, and as previously stated in preceding sections, the share of coal in the global energy mix in the coming decade will remain prominent (perhaps declining only by 1% between 2016 and 2022, from 27 to 26%). Most of the growth is likely to occur in India and ASEAN countries. With declining demand in Europe and Canada and uncertainties in USA and China, IEA forecasts coal demand to reach 5530 Mtce in 2022. Despite the global concern for climate change and a stated wider consensus on action following the 2016 Paris climate agreement, global coal-fired power generation is forecast to increase by 1.2% per year, with share of coal in the power mix falling to 36% due to rapidly falling gas prices and possibly more output from renewable energy sources.
projects. Countries such as Pakistan, Bangladesh, and Indonesia are predicted to significantly increase their consumption of coal between 2016 and 2022.

China’s policy and economic restructuring is aimed at ‘making its skies blue’, despite a projected increase in coal-power generation. Coal is expected to supply over 55% of China’s energy demand in 2022. Meanwhile, with Indian mines running at less than 60% of capacity, which is predicted to improve with an ongoing structural reform in mining practices and increasing pressures from electrification, coal-fired generation in India is forecast to increase at 4% per year through 2022.

Fast-paced economic growth will see a steep increase in the consumption of coking coal, driving a 5% increase in its import per year through 2022 in the country (IEA, 2017). Many south-east Asian countries have already emerged to provide the fastest growing demand hub for energy, recording over 150% increase in energy demand over the past 25 years, and predicted to reach 1070 Mtce by 2040. During this period, the electricity demand nearing 1104 TWh is forecast, half of which is forecast to come from coal (WCA, 2005). It is noteworthy to mention that 120 million people in ASEAN countries currently live without access to electricity according to WCA 2016 estimates.

Coal, in the USA, is no longer in total retreat, with the introduction of new measures and reforms by the Federal Government and announcements by the recent Trump administration to deliver ‘1000 years of clean coal’ (CNBC, 2016). Coal production in the USA is forecast to be around 510 Mtce in 2022, while demand is likely to decline at an average of 1% per year through 2022. US will remain a swing supplier into both Atlantic and Pacific markets, and according to the forecasts, will exhibit the highest uncertainties of all coal exporters. Australia, Indonesia, Russia, Colombia and South Africa are predicted to be the top exporters. The USA is active in seeking a reportedly cleaner solution in coal production, and close to operating completion of a new plant in Wyoming using their Powder River Basin deposits (CCTI, 2018). The issue is of interest to Asian-based coal users. The future of coal in the twenty-first century will be significant both in driving growth in developing countries and in thereby potentially contributing to climate damage. Coal will also cause significant movements in energy geopolitics by changing established patterns of demand and supply and trade flows. Future trading instruments will play a key role maturing coal markets. While coal provides a secure and affordable supply of energy, more political will and significantly higher investments are required to support a successful transition towards lower emission coal technology if coal is to play a part in the journey to decarbonisation. Financial and technological investments towards the deployment of carbon dioxide capture, utilisation and storage (CCUS) will be needed if there is to be a longterm future of coal, although to date cost implications have caused hesitation in pursuing this approach.
Policy priorities pursued by the biggest demand centres will, more than anything, determine growth, stagnation or decline in demand for coal or more interest in its conversion to gas or liquid. In recent years, much concern has been raised regarding the growing coal consumption and usage in China and the associated GHG emissions. Arguably, over the past two decades, China has built prosperity on the basis of coal in a way that took Europe and America almost 200 years. However, at this point in time there is evidence that China may finally be deeply and sincerely acting to address the harmful environmental consequences of untreated coal combustion.

India, on the other hand, is less often presented as the face of the global carbon problem with continued assurances from the government, including the recent indication by Prime Minister Modi that the country will go ‘above and beyond’ the Paris agreement. India’s sincere efforts to provide ‘Universal Electrification’ and promote ‘Make in India’ is driving strong growth in unabated coal combustion. Despite recognising the potential of climate threat globally and committing to take concerted action to transit to a cleaner energy pathway, India has not yet chosen to follow China towards beneficial technical innovation, due to a range of conflicting political realities and priorities.

Unfortunately, it cannot be said with clarity whether India in 2050 will be in a better place than it is now. There is a risk that if India does not act soon and start embracing clean coal technologies more seriously and move more aggressively away from fossil fuel use, it will assume the status of the world’s biggest polluter.
Chapter 6. A System Dynamics Based Analysis into the Effect of Dynamic Feedbacks between Energy Policy Objectives in India on Coal Power Generation and CO\textsubscript{2} Emissions

Context

A substantial reduction in CO\textsubscript{2} emission must be achieved to reach net-zero by 2050 and limit the global temperature rise to 1.5 °C (IEA, 2021). According to the International Energy Agency report, despite being structurally and systematically phased out from the energy mix of many developed countries, aided by a mix of environmental policies and mounting competitive pressures from other energy sources-most notably renewables, coal will remain a vital component of electricity generation in the foreseeable future. Currently, coal-fired power fuels around 37\% of global electricity and will continue to be the single largest source of the world’s electricity with its set contribution of 22\% in 2040 (IEA, 2021). Electricity demand is set to increase with growing prosperity and rising household incomes, electrification of transport and heat, and growing demand for air conditions with rising temperatures. Given the share of coal in the current electricity generation mix, as demand for electricity increases, CO\textsubscript{2} emissions will increase with an irreversible impact on the global climate. In 2018, rising electricity demand was a key contributor towards global emission of CO\textsubscript{2} accounting for nearly two-thirds of emission growth. Of the total estimated 33.1 Gigaton (Gt) CO\textsubscript{2} emitted in 2018, emissions from coal use in power were estimated to have crossed 10 Gt, emerging mostly from Asian countries, and notably, China, India and the United States contributed to over 85\% net increase in emissions (IEA_Publications, 2019).

Despite the widely heralded end of the coal era in many parts of the world, the IEA (2019) report point out that coal’s consumption is poised to remain strong in many Asia countries, more specifically India. India is already the third-largest carbon-emitter in the world; the third-largest energy consumer in the world after China and the United States in 2018, according to the BP Statistical Review of 2019 (EIA, 2019). That said, emissions from coal-power in several other places, including Germany, Japan, Mexico, France and the United Kingdom, and spending on coal-fired power and investments in new coal plants continue to decline, and after registering growth for three years in a row, a 3\% drop in coal-fired power generation was seen in 2019 due to slump in electricity demand growth (Malischek, 2020). Although this decline is promising, widespread concerns prevail
over continued reliance on coal in Asian economies, where coal’s share in electricity generation was estimated at 36% in 2019 (IEA, 2021).

There, however, is no denying that renewables, together with fuel-switching measures, will continue to change the electricity generation landscape globally, this transformation may be more pertinent in some parts of the world and less so in others where emission reduction may be more difficult to achieve. In exploring the deep decarbonisation of electricity generation India serves as an interesting and very relevant case study.

India’s need for energy supply is poised to increase as a result of the country’s dynamic economic growth, population growth, and modernization over several years (EIA, 2019). India’s policies to provide ‘last mile electricity’ to all by 2022, promote ‘Make in India’ boost to the manufacturing sector, and rapid urbanisation will see a further increase in electricity demand growth, creating triggers for rapid expansion of the country’s power generation capacity. Driven by its’s socio-economic and political realities, coal is likely to remain the mainstay of India’s power generation for many years to come. With over 74% electricity generated from coal, the electric power generation Emissions from India’s power sector remains a focal area for emission reductions.

India has pledged to reduce its carbon emission footprint by 30-35% from its 2005 levels by 2030 and has set a target of generating 450 gigawatts of renewable energy by 2030. Balancing the objectives of affordability, environmental sustainability and greater reliability on endogenous energy sources are each difficult policy objectives to achieve in the set time-frame by themselves; the need to achieve them all together with equal priority and urgency makes India’s energy transition rife with uncertainties and challenges.

This chapter focuses on the problem of rapidly increasing CO₂ emission from increased coal-based power generation in India and answers the second sub-question proposed in Chapter 1: What will be the impact of India’s overlapping energy policy objectives on coal use for power generation and India’s carbon emissions pathways?

A system dynamics model is developed to access the feasibility of emission reductions under the current economic and power generation expansion plan and to identify leverage points for effective policy intervention. While reducing emission intensity may be possible, with significant policy push, the aim of this study is to examine the impact on CO₂ emission reduction. A systematic SD-based approach can reveal possible system structure trajectories, provide deeper insights and assist the understanding of systemic interactions, while recognising evolving challenges and behaviours. Various existing documents, policy white papers, industry reports, annual reports by the Indian
Government and market trends and outlook are analysed to set the relevant boundaries for the model.

**Overview**

India is the world’s third-largest economy in PPP terms (fifth largest in nominal terms) and the second-most populous country (IEA, 2021). According to the United Nations, by 2027 India is predicted to leave China behind becoming the most populous country in the world, with a population of over 1.5 billion people (UN, 2019). India’s economy is expected to grow from per capita GDP (nominal) USD 1408 in 2016 to 4205 in 2030 (Government of India, 2016). Since 2000, over 10% of the increase in global energy demand has been brought about by India, and India is projected to remain the largest source of demand growth out to 2050, growing between 2.5%-3% per year (BP, 2021).

While this strong growth promises immense opportunities for India, there are significant challenges that need addressing. India is home to 24 percent of the global population without access to sustainable, secure and modern energy sources and a rapidly growing population base (World Bank report). India aims to pursue policies and strategies to achieve better standards of living, and financial and social inclusion for its entire population (WB, 2019). Significant efforts to achieve Universal Electrification by 2022 are underway (Mallapur, 2018). India also aspires to increase the share of manufacturing in GDP from 16% in 2017 to 25% by 2022 to bring down the country’s import dependency on oil and coal (National Energy Policy, 2015).

Energy is undeniably crucial for India’s growth and development, its energy use has doubled since 2000 (IEA, 2021). And while India has made huge strides in improving electricity access, providing electricity access to 750 million people between 2000 and 2019, World Bank figures show that 200 million people still lack access to electricity (WorldBank, 2018). Jain (2016) estimates that 54% of households in India lack electricity access, while about 89% of rural households depend on polluting energy sources. India’s ambition to improve energy access and eradicate fuel poverty will be significant for determining the success of the United Nation Sustainable Development Goals, notably Goal 7 on delivering energy access (IEA, 2021).

Despite being the third-largest emitter of carbon emissions, India’s per capita energy use is currently much lower than the OECD and the world averages (IEA, 2021). It is, however, predicted to significantly increase over many decades. As India pursues its development ambitions steered by a growth-conducive policy regime, the landscape of its energy demographic will change. According to the British Petroleum Energy Outlook, rapid urbanization and improvements in prosperity for
millions of Indians is predicted to increase India’s share of global primary energy demand to nearly double to around 11 percent (from 6 percent currently) by 2040 (BP, 2019). Studies (World Bank, 2018; IEA, 2021) suggest that India will need to add a power system the size of a European Union to what it has now to meet the growth in electricity over the next twenty years to meet the energy needs of its rapidly increasing population.

BP predicts that nearly half of India’s new energy demand is likely to be fueled by coal, and despite a sharp increase in the installed renewable capacity, coal will account for 80 percent of electricity output in 2040. Coal is predicted to dominate India’s power generation mix in the outlook period (ibid). This results in an almost doubling of India’s net CO₂ emissions to 5Gt by 2040, which increases to 14 percent of global emissions by 2040 (from 7 percent currently), a worrying prospect for global climate (BP, 2019). BP’s emission forecasts for India are somewhat more conservative compared to other studies that predict much higher levels of CO₂ emissions, some indicating that India’s CO₂ emissions may reach 4.0-7.3 GT by 2020 (Planning Commission, 2011); 8 GT by 2050 (GICC, 2013).

India is a major factor in the fight against climate change globally. At the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties in Paris (COP21), India set out its intentions, commonly known as Intended Nationally Determined Contributions (INDCs), to transit to cleaner systems and achieve environmental sustainability. This includes an ambition to reduce the emission intensity of its GDP by 33 to 35 percent by 2030 from 2005 level and to have non-fossil fuel based energy resources make up about 40 percent cumulative electric power installed capacity by 2030 besides facilitating extensive afforestation to create an additional sink of 2.5 to 3 billion tonnes of CO₂ equivalent by 2030 (UNFCCC, 2015).

Curtailing CO₂ emissions in India’s coal-fired power generation can be challenging, as India undergoes rapid industrialization and urbanization, but needed to meet global NetZero targets (UN, 2018). The power sector in India has been undergoing significant transformation with the rapid growth of renewable energy which has grown from almost nothing in 2000 to 84 GW of Renewables based capacity in 2019 (PowerMin, 2020). However, the projected renewable energy development, or outlined ambitions, may not be enough on its own to meet India’s rising electricity demand. Coal-fired power plants may still be necessary for the foreseeable future, reinforcing the challenge of restricting emissions growth in India.

The need to assess energy systems transition from a wider systems perspective to frame policies that are effective in concurrently addressing issues like sustainability, security and affordability of energy resources becomes more relevant. Several aspects need careful examination, and questions
diligent answering, if India’s energy policy is to deliver its set objectives with any degree of success. These issues include, but are not limited to, cost-competitiveness of new renewables, the role of coal and oil, uptake of nuclear power in helping supplement coal-based capacity (as base load in the interim but potentially substituting it in the future), existing and emerging market signals and trade relations etc.

Many studies also highlight the importance and attractiveness of gas-based power generation in reducing CO₂ emissions in India (IEA, 2021). However, it is more expensive to generate one unit of electricity with gas than with coal. Furthermore, India has limited reserves for gas, and despite the launch of campaigns such as Gas4India to boost the uptake of gas, its estimated share in the total energy mix is expected to rise from about 5.76% in 2019 to 7.4% by 2025 (below 8% by 2030). Coal’s cost competitiveness and availability will also impose significant infrastructural and pricing hurdles to any large-scale integration of gas-based installed capacity with existing generation system (Mohanty, Kanoi, & Hui-Min, 2019). With abundant reserves of coal in the country, and its cost advantage over other energy sources including gas, the government’s Planning Commission deems it unlikely that gas can contribute a large share of electricity generation in the foreseeable future (Planning Commission, 2011). While each of these issues will significantly impact the global NetZero ambitions; the enquiry undertaken in this chapter is restricted to the emission reduction potential of India’s predominantly coal-based power generation pathways to help provide unintuitive and evidence-based policy making to address the issues of the energy trilemma.

Given India’s growth trajectory and the stated ambition to achieve affordable, secure and environmentally sustainable supplies of energy to fuel its growth, coupled with an obvious infrastructure deficit needed for achieving all the sought policy objectives, coal plays a prominent role in India’s energy future. India’s share of world fossil fuel reserves is relatively low, with 0.9% of world crude oil production and 0.9% of natural gas compared to its coal reserves (Spencer et al., 2018). The high import dependency on fuel is an important macroeconomic vulnerability for India. According to Spencer et al. (2018: 6), ‘India’s net energy imports have averaged about 4% of GDP since 1995, reaching peaks of 7-8% of GDP in 2008, 2011, 2012 and 2013’, and ‘during periods of high international energy prices, [these can] put significant pressure on account deficit, currency valuation, inflation, interest rate, and on growth’. Coal, on the other hand, presents the potential to significantly reduce India’s exposures to these risks by reducing India’s dependence on imported gas and oil and also hedges against the price and supply volatility of oil and gas supplies (ibid). Besides electricity generation, coal is also used directly in the industry sector, both as a fuel in industry as well as raw material in the production of steel (details in Chapter 5). India is also the world’s second-
largest producer of coal, providing approximately half of the country’s primary energy supply and contributing to roughly 74% of India’s electricity (BrookingsInstitutions, 2019). It is also an important economic sector. According to Coal India reports, coal mining directly employs around 500,000 people and support their families in some of the most economically backward states (CIL, 2018). Spencer et al. (2018:8) estimate that in 2015 the value of coal and lignite sector accounted for 37% of the nominal value of the gross output of India’s mining sector, which in turn made up about 2% of the Indian economy. The coal sector, therefore, accounted for about 0.7% of the Indian economy in 2015. Despite contributing a relatively smaller share directly to the Indian economy, its role in power generation and as an important source of economy in the states where it is mined is undeniably vital.

Given its likely role in the future global energy landscape, India’s energy pathways are an active research area for several international agencies. These studies offer a closer look into various projected outlooks likely to evolve from different policy trajectories. BP’s India outlook predicts strong growth in India’s primary energy consumption across all its scenarios between 2018-2050, the share of coal in total primary energy consumed ranges between 5 to 40% in its scenarios based on policy trajectory. Carbon emissions in the current (or Business as Usual) policy scenario increases by around 90% in 2050 (but decreases by 53-99% in other scenarios that factor in extreme policy changes) (BP, 2020). The variation projected by BP India Outlook is staggering with India’s carbon emissions falling in the range between -99% to +90%, and coal’s share between -80% to +83%. The IEA’s World Energy Outlook (IEA, 2021) in its Stated Policies Scenario projects India’s electricity demand to grow by 5% per year to 2040 and carbon emissions by 50% (offsetting the projecting decline in emissions in Europe). Most of these global studies on India take a composite overview of all the sectors. A study that focuses on aspects related to increasing emission from coal generation emerging from India’s overlapping energy policy objectives is not available, a gap that this chapter seeks to address. Given electricity generation from coal is a major contributor to rising emissions examining the impact of current policies is of key significance as examined by this chapter.

The objective of this chapter is to capture the dynamics of emerging trends and pathways by modelling the uncertainties in India’s energy landscape and policy directions. The relevance and suitability of SD to this research has been established in previous chapters. A novel System Dynamics (SD) model is developed to analyse the impact of overlapping policy objectives in India on globally desired outcomes of environmental sustainability. As is the case with System Dynamics models, the model presented in this paper does not provide a forecast of what will happen, instead, it provides a set of scenarios that help to explore different possible futures and understand the system structure,
and the interconnections between different parts of the system, that bring them about. The SD technique is particularly useful in revealing possible system structure trajectories and systemic behaviours based on complex component interactions with feedbacks and time delays.

The model considers policy signals, time delays, non-linear causal relationships and concurrent interactions between the two dominant power generation sub-systems in India. The model specifically focuses on the problem of rapidly increasing CO₂ emission from increased coal consumption in India arising from steep growth pressures on energy demand. The insights gathered from this model will also help to assess the efficacy of the current global governance framework in facilitating energy systems decarbonisation. This study thus provides an evidence-based lens for examining the current gaps in the governance framework globally.

**Model Development**

An India coal model is developed between the time horizon of 2000 and 2050 to examine the impact of carbon emissions from coal-based generation in India. The selection of the time horizon for the model has been rationally done to capture the delayed and indirect effects of potential policies extending far out into the future to address challenges associated with the event-oriented worldview (details on time-horizon selection in Sterman (2000:90-94). Major changes have taken place in India’s power generation sector since the early 2000s, including the adoption of renewables-based energy for power generation. As set out by the IPCC, ‘global net human-caused emissions of carbon dioxide (CO₂) would need to fall by about 45% from 2010 levels by 2030, reaching ‘net zero’ around 2050’ (IPCC, 2018). BP Energy Outlook for India estimates that a growth in India’s renewables-based generation-driven largely by solar capacity may succeed in lowering the carbon intensity of India’s power grid, declining by 29% in 2040, however, with coal’s projected dominance in the country’s power generation mix, the share of global emissions increases to 14% (BP, 2020).

Based on the prescribed SD methodology, the selection of necessary set of elements that generate and present the behaviours of interest based on careful study of available reports and literature. Elements that do not directly generate the variables of interest were cautiously omitted or excluded from the model (Sterman, 2000). In John Sterman’s words, ‘models must have a clear purpose, the single most important ingredient for a successful study...to solve a particular purpose; [...] and knowing what to leave out of a model, is the [essential] art of model building’ (Sterman, 1988, p. 5). Given the prominence of coal and renewables-based installed capacities on India’s CO₂ emissions from power generation, these constitute the key sub-systems of the model developed. Elements that interact with other elements within these sub-systems are modelled as endogenous variables, while those that do get sufficiently impacted by elements within the system but not calculated by
the model, are brought in as exogenous variables (Sterman, 1988). An important part excluded from this model is the price and market mechanisms of different electricity sources. While the cost and profit may impact the investment and development of generation infrastructure, most aspects of India’s generation systems are currently centrally regulated. Despite some recent attempts to deregulate certain parts of the generation system through the launch of transmission-line tenders and competitive solar biddings, the majority of the investment is done by the Government (PowerMin, 2020). Import and export of electricity are much insignificant and therefore deliberately ignored. Compared with coal power plants, carbon emissions from Renewable Energy Sources (include small hydro projects, biomass gasifier, biomass power, urban & industrial waste power, solar and wind energy) are much lower and therefore these are neglected.

The main drivers of total electricity demand in the model are GDP growth, population growth and desired per capita electricity demand growth. Apart from Renewable Energy Sources most of the electricity demand is fulfilled by coal-fired power plants (India additionally also has 10% of hydro capacity-which is not included in the Renewable Based Capacity, 4.5 % gas and 1.8 % nuclear). Key variables are presented in Table 6.1.

<table>
<thead>
<tr>
<th>Endogenous Variables</th>
<th>Exogenous Variables</th>
<th>Omitted Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal capacity; coal capacity under construction; renewable capacity; renewable capacity under construction; desired per capita electricity demand; desired total coal capacity; desired renewable capacity; accumulated CO(_2) emissions; pressure to add additional capacity; capacity adjustment to demand.</td>
<td>renewable capacity target; coal target; India’s desired emission target level; coal emission factor; net population growth rate; GDP growth rate; fractional growth rate in electricity demand; revised renewable capacity target</td>
<td>Other sources for power generation; cost parameters</td>
</tr>
</tbody>
</table>

**Reference Mode of Behaviour and Dynamic Hypothesis:** The reference mode of behaviour in this model is the trend in carbon emission growth over time from India’s power generation sector. Coal demand in India, according to the International Energy Outlook’s India Energy Outlook and as previously stated, is predicted to increase more than two-and-a-half times in 2040 compared to 2015 levels. This increase in coal consumption is expected to be a major factor behind the dramatic rise in India’s related CO\(_2\) emissions, and a key contributor to the aggregate increase in global emissions (IEA, 2015). Many outlooks and reports include several scenarios, including those issued by some of the nodal ministries of the Government of India, that explicitly and implicitly signal a planned replacement and a systematic phase-out of coal-based installations for electricity generation and its replacement with alternative energy sources. However, no indicated plans on the sources of investment or concrete feasibility analyses have been offered. Given India’s expected
population and economic growth, and the goal of energy poverty reduction over other energy policy objectives, this study proceeds with the assumption that in a business-as-usual scenario coal continues to dominate India’s energy mix and remains the major source of CO$_2$ accumulation (Garg and Shukla, 2009) of not only of India’s contribution but of emission accumulations seen globally.

To show the fundamental relationships between various elements of the model and the dynamics between these key parameters, a causal loop diagram is developed, provided in Figure 6.1. These feedback loops represent the dynamic hypothesis of the problem of incremental CO$_2$ emission growth from energy sources in India and account for the stocks and flow variables within the system believed to be responsible for this increase. The dynamic hypothesis is centred on feedbacks between the following loops:

- **The reinforcing energy-demand-growth-in-India-loop**: This loop represents the growth in power generation (both coal and renewable capacity installation) to sustain India’s growing energy needs. This capacity expansion is aided by policy support through a variety of policy tools, such as through a growth in subsidies, and policy signals influencing indicated investment in generation capacities. Rapid growth (population and economic) and improved energy access will drive the increase in both coal and renewable-based electricity.

- **The balancing India’s-climate-target-loop**: India’s ambition to reduce its carbon footprint by 33-35% from its 2005 levels by 2030 has mandated efficiency improvements, aided through the adoption of targeted policies (such as India’s Perform, Achieve and Trade (PAT) scheme- a regulatory instrument to reduce specific energy consumption in energy-intensive industries (BEE, 2020)), higher investment in super-critical (SC) and ultra-supercritical (USC) coal-fired power plants, and changes to the regulatory landscape to increase competition and deregulate parts of the power sector. As global pressures to decarbonise increase, older sub-critical coal power will be phased out and replaced by cleaner technologies with lower carbon emission factors will reduce CO$_2$ emissions. This will have the potential to stabilise, in some scenarios even reduce, CO$_2$ emissions.

- **The balancing renewable-growth-loop**: Increased uptake of renewable capacity has a negative, or balancing effect on CO$_2$ emissions; it makes it possible to bring down coal’s share in installed capacity; reduction in coal capacity beyond a point will cause capacity shortfall and will drive a growth in coal capacity, and an increase in emissions.

- **A future reinforcing clean-coal-loop**: This is a forward-looking policy, premised on one of the projected future scenarios that India proposes to undertake to meet its social, political
and economic aspirations and realities. This is introduced in the model to test the effectiveness of this policy in meeting Net Zero objectives.

Figure 6.1: Feedback loop diagram of the problem of unabated CO$_2$ emission from increasing energy demand in India. (The dynamic hypothesis of the model, as previously stated, is based on the interactions between: the India-Demand-reinforcing-loop; the renewable-growth-balancing-loop; the India-Climate-Target-balancing-loop and the clean-coal-reinforcing-loop.)

Because of both balancing as well as reinforcing loops in the model, the key variables will likely exhibit an s-shaped growth (details on SD archetypes and behaviour exist in Chapter 2). These loops describe and reflect the structure and relevant interactions between various key parameters within India’s energy structure. The balancing and reinforcing loops, as shown in Figure 6.1, interact to produce the S-shaped growth trajectory for CO$_2$ emissions as seen in Figure 6.2.

Figure 6.2: Rising CO2 Emissions from India’s Power and Energy Sector
(Note: There is variation between various sources in estimated emissions, however, this study is more interested in the emerging trajectory than in the exact data point.)
Sub-models

The model consists of three sub-models: power demand sub-model; power generation sub-model and CO₂ emissions sub-model. Their interrelationship and feedback can be summarized as follows: power demand determines its supply (generation); the make-up of power generation determines the amount of CO₂ generated; the growth in emission influences the growth in alternative and cleaner sources of generation. Each sub-model is described below.

1. **Power demand sub-model**: The power demand structure is constructed to represent the upward pressure on electricity demand created by India’s GDP and population growth. The relationship between GDP growth, population growth and increase in energy consumption; and the resulting impacts arising from these interactions have been a subject of many detailed studies and have been considered a given (details can be found in Holdren & Ehrlich, 1974; Kraft & Kraft, 1978; also Brundtland, 1987; Meadows & Randers, 2012). In the model, industrial and household electricity consumption constitutes the total electricity consumption. As electricity demand increases there is pressure to add additional capacity, which signals policy makers to evaluate the available capacity and plan investments to avoid any future shortfalls. In India’s context, Coal India Ltd. (the main subsidiary of the Government of India responsible for production, allocation and distribution of coal through other central and state government undertakings) manages to supply the desired stocks of coal at the plant sites as required, and any deficit or demand-supply imbalances in desired domestic coal is met by imported coal. GDP and Population are both modelled as stocks with net inflows of their respective growth rate. Data from Central Electricity Authority, World Bank and BP Statistical Review is used to calibrate the model.

2. **Power Generation sub-model**: The sub-model for electricity generation capacity consists of three key components: a coal-capacity component; a renewable-capacity component; and finally, a ‘clean-coal’ capacity component. Each of these components is modelled using the respective capacity and capacity under construction stock with relevant inflows. The addition and retirement of coal, renewable and ‘clean coal’ capacities are modelled by using the standard stock management structure (Sterman,2000: 675-683). The stock management structure provides insights into the behaviour and sources of amplification observed in supply chains: a delay between the desired and actual addition of capacity impacts the stock of coal capacity, which increases with coal capacity additions and decreases with their retirements. The capacity addition is formulated in the model as a first-order delay and depends on the indicated investments determined in turn by policy decisions that seek to balance various sought goals. When desired stock increases, the desired cc addition rate increases through the coal capacity
stock adjustment loop. Standard goal-gap formulation is used in each of the generation submodels, and policy targets and published data from BP Statistical Review and annual reports published over years by the Power Ministry of India and Central Electricity Authority are used.

Total coal capacity is modelled as the desired rate of coal capacity addition, which considers domestic policy goals such as growth in per capita electricity consumption, renewable capacity target, as well as desired fraction of clean capacity addition. Both coal and renewable generation in India receive significant shares of policy support, modelled as policy boost on coal subsidies and subsidies support for renewable capacity growth. Given the lack of robust data on subsidies, non-linear formulations have been used to represent these in the model. Despite falling renewable prices, problems around its storage and intermittency remain and it is highly unlikely that an expansive replacement of coal capacity with renewables will be possible. These realities have been captured in the model by allocating suitable fractions to coal and renewable generation capacities.

3. CO₂ emission sub-model: The structure for CO₂ emission is modelled as a stock with an inflow of emission growth rate. This emission factor for clean coal-fired power plants enabled with CCS is very nearly zero, while it is much higher for sub-critical coal units. The amount of CO₂ emission from each of these units equals the amount of electricity generated multiplied by the corresponding emission intensity. A policy SWITCH regulates the shift from clean coal capacity towards clean-coal capacity with CCS. When the SWITCH is OFF, the emission levels increase corresponding to the indicated growth in conventional coal capacity, but when it is ON, the policy makers compare the CO₂ emissions stock and the INDC’s target and initiate necessary adjustments in coal capacity, such as via support being made available to cleaner and more efficient coal-fired power plants. The full model structure is presented in Figure 6.3.
Figure 6.3 Full Model Structure for India Coal Power Capacity and CO₂ Emission Dynamics
Model Validation

Model validation was carried out to build confidence in the model. Both the structural validity and behaviour validity tests were carried out to determine the suitability and adequacy of the model to the system represented and the problem analysed. To determine the robustness and validity of the policy model, its development followed the prescribed processes of problem formulation and identification of a clear dynamic hypothesis. The boundary of the model was carefully determined through meticulous selection of parameters that could directly impact the behaviour of the system.

The time horizon of the model was selected based on the longest time delay to help capture long-term trends, which in this case was 2050, the timeline for achieving Net-Zero emissions. Sterman (2000) explains the importance of careful boundary selection and variable classification as endogenous (arising from within), exogenous (originating outside) and excluded (not significant to the point of enquiry). As the main point of enquiry is to analyse the impact of coal-capacity growth on CO$_2$ emission reduction targets, the time horizon extends between 2000 and 2050.

As Barlas (1989) suggests, statistical tests may not be entirely appropriate and suited to test the validity of system dynamics models, rather tests that assess the behaviour pattern are better suited for behaviour evaluation. Therefore, pattern-matching between simulated behaviour and historical data was carried out to assess if the modelled behaviour followed the same trajectory as the historical data. The model was also tested for dimensional consistency and was found to be dimensionally consistent. To validate the model, the outcomes of the model are compared with the available historical data from Central Electricity Authority for coal (see Figure 6.4) and renewable generation capacities (see Figure 6.5) and BP Statistical Review for CO$_2$ emissions (see Figure 6.6). The results of the comparison between installed coal capacity, renewable capacity and CO$_2$ emissions from power generation (presented in Figures 6.4, 6.5 and 6.6) show that the simulation results closely follow the same behaviour pattern of the historical data. As may be seen in these figures however, the simulation lines do not exactly fit to the historical data. The behaviour after the start of the simulations in 2000 is generated by the model without awareness of real-world developments, and the minor deflections are entirely acceptable. The long-term behaviour exhibited by installed coal and renewable capacity is consistent with the desired target set by the Government. These comparisons establish the ability of the model to mimic reality, at least over the initial years after the model start.
Sensitivity testing (or analysis) of the model was done to find out if the general pattern of behaviour is strongly influenced by changes in uncertain parameters (Ford, 1999: pp281). In doing so, the exogenous inputs and minor assumed parameters were selected for adjustment, and simulations were run with changes in these inputs. Changes in these variables did not alter the fundamental tendency of the model behaviour, thereby proving that these parameters were indeed less important to the overall model structure and that the model does indeed capture the essence of the problem endogenously.

The model also passed extreme condition testing, which was performed to check whether the model outcomes make sense under extremely stressed conditions by setting the birth rate to zero (a wholly implausible scenario). Stress testing showed that if the birth rate in India is set to zero, the model runs and indeed significantly less energy is needed. In such an impossible scenario it would be possible to meet the energy requirements with a negligible share of coal capacity. The observation that a coal-free future in India is possible, is we suggest, of a similar level of realism as a scenario in which the birth rate drops to zero. The former outcome is utopian and the latter dystopian, but neither is going to happen. More importantly for policy, these tests establish that the model is robust as the results under extreme conditions remain valid.
**Scenario descriptions:**

Within the scope of the model the effects of increasing electricity demand, and a desire to reduce CO₂ emissions have been evaluated. The impact of changes in policy signals (through the use of SD switch variables), policy decisions, desired capacity changes, desired levels of emission reduction targets on accumulated emissions (through coal and renewable capacity) have been examined in our SD simulations.

The *reference scenario* examines a ‘business as usual’ scenario based on the current policy landscape. It represents the most likely behaviour under the current policy scenario if no drastic changes in the policy landscape are introduced. In this scenario population growth rate is set to the projected growth rate by the World Bank, the GDP growth rate is set as per India’s projected growth rate. The baseline simulation of installed coal and renewable capacity is presented in Figure 6.7.

![Figure 6.7: Simulated estimates of India’s projected renewable and coal capacities in Reference Scenario.](image)

The modelled projection for India’s installed renewable capacity is consistent with India’s Centre for Science and Environment figures that estimate that India’s installed renewable capacity will reach 250-300 GW in 2030. Somewhat notably, the modelled result shows that it will not be feasible, under the current policy conditions, to realise the desired renewable energy target of 450GW capacity by 2030. As reported by the Power Ministry (PowerMin, 2020), India’s renewable capacity in 2020 is 85 GW, PowerMin (2020), significant efforts will be needed to realise the stated ambition of 429% increase over the next ten years. A report by the Institute for Energy Economics and Financial Analysis (IEEFA) estimates India will need around $500 billion (£360bn) in additional investment to reach the target of 450GW of renewable capacity by 2030, of which approximately $300 billion (£216bn) will be necessary for wind and solar infrastructure, $50 billion for grid firming investments, and $150 billion on expanding, modernising transmission (Buckey, 2019).

Redirecting this additional funding towards implementing low emission coal technologies can have a wider and longer-reaching effect towards achieving Net Zero objectives. In its India Outlook, IEA (2021) estimates that India will need $1.4 trillion (£1tn) in additional funding for low emissions.
technologies over the next 20 years in order to be on a sustainable path over the next 20 years. This translates to roughly 70% higher investments than currently available in the Reference Scenario.

The base case of emission intensity is shown in Figure 6.8(a). The emission intensity of India’s GDP is observed to undergo a steady downward trend, decreasing by almost 28% from 0.72 million tonnes CO$_2$/Billion USD in 2000 to 0.51 million tonnes CO$_2$/Billion USD in 2030, and by 38% to 2050 reaching 0.44 million tonnes CO$_2$/Billion USD. This is in line with India’s climate pledge to cut the emission intensity of its GDP by 30-35 per cent by 2030 and as shown by the modelled simulation that India may be successful in meeting its Paris commitments.

But even as India’s emission intensity does reduce significantly in the business-as-usual scenario, there is an increase in CO$_2$ emissions from India’s electricity generation between 2000 and 2050, hence the Reference Scenario indicates a basis for global concern, if India were to continue with a business-as-usual approach.

The Reference Scenario is consistent with India’s policies that are aimed at lowering its emissions intensity in accordance with its Nationally Determined Contributions. During this time, systemic efforts to eradicate energy poverty in India are also undertaken. The business-as-usual assumptions include several key considerations such as installation of super-critical coal plans and a higher uptake of renewables and are not a ‘do nothing’ scenario. This gradual change in India’s power generation landscape is shown by the change in the fraction of coal and renewable capacities in the reference scenario in Figure 6.9. Rise in emissions exacerbates the ongoing concern over India’s energy policy choices and explains the growing pressures demanding tangible actions through quantifiable changes in its energy consumption-production patterns.
As shown by the simulation result, a deep decarbonisation or a Net Zero transition of India's power generation pathways will not be possible based on the current configuration and policy choices in India. India’s emission from coal-based power generation alone increases to roughly 4 billion tonnes in 2050. The overall emissions from India’s energy sector are estimated to be much higher, as the modelled simulation only allocates 30% of the total carbon emissions against emissions from electricity generation. These results present a grim prospect for decarbonisation objectives. The Reference Scenario will however enable the production of cheap and reliable energy. Slower economic growth does help to reduce India’s CO₂ emissions by reducing electricity demand. This scenario also glides over any external pressures necessitating policy reforms to bring down emissions. The steep growth in coal and renewable capacities is reinforced by policy interventions.

An India Growth Scenario is run to test the impact of two significant growth drivers, GDP growth rate and urbanisation, on CO₂ emissions. One might take the view that the most likely alternative scenario to the Reference Scenario, as presented, is one with deeper climate action. That is not obviously true. In this scenario, a higher uptake in renewable capacity is introduced by adding higher subsidies to boost the capacity. India’s coal generation capacity increases from 6GW in 2050 in the Reference Scenario to over 8 GW in 2050 in this high growth scenario. Approximately 25 per cent of the coal capacity in 2035 consists of higher efficiency low emission technologies. As a combined result of these two factors, despite a significant increase in coal capacity, the impact on CO₂ emissions growth is less severe. Simulated results from the scenario are shown in Figure 6.10.

This presents a significant prospect for Indian coal-based generation capacity. This scenario favours higher economic growth, greater urbanisation and efficiency gains in India’s coal-fired power plants. CO₂ emissions, in the meanwhile, continue to grow reaching 4000 million tonnes in 2040.
Policy Analysis

The scenarios presented above confirm that, in the absence of major new targeted policy measures, Indian CO$$_2$$ emissions from coal-based electricity generation are poised to increase in the foreseeable future. It is therefore essential to test the efficacy of policies that could prove effective in restricting growth in emissions from coal power plants. Two possible ways are explored through which it may be possible to decarbonise India’s electricity generation pathways - through subsidies reform, and a hybrid scenario mediated by stringent climate action.

**Subsidies reform**: India has a unique social, political and economic situation and the nation’s energy future is currently determined by top-down policy signals and changes in the regulatory landscape (NEP, 2015). A key leverage point that can potentially reform India’s power sector is through subsidies reform.

Subsidies are one of the most important policy instruments that the country currently uses to shape its energy mix. Energy subsidies are a cost to the central and state governments: directly, in the case of fiscal transfers, or indirectly, in the case of policies such as tax exemptions, credit guarantees or the provision of government good and services at below market costs (IISD, 2016). Subsidies can be a great enabler, however, if not well designed, targeted and monitored, they may: fail to meet objectives; distort markets in negative ways; benefit unintended groups who do not need assistance; encourage wasteful and polluting energy consumption; and be very expensive, taking up scarce resources (Beaton et al., 2013). Subsidies may also lock the country into expensive and polluting technological options in the medium to long-term with huge social and environmental externalities.

The strong growth in renewable generation in the recent years, from 12 to 17.5 percent of total installed capacity between 2012 and 2017, has been largely driven by a range of subsidies amounting to a total value of USD 1.4 billion in FY2016 to accelerate its deployment, in turn, driven...
by the government’s renewable energy targets (ibid). By redirecting subsidies towards high-efficiency-low-emission technology India can manage to lower its carbon emissions.

**Hybrid Scenario - Reference Growth with Climate Action**

The Reference Scenario and the delayed use of the policy switch favouring clean coal revealed an outcome of a dramatic increase in net CO₂ emissions. A separate scenario study showed the harmful growth in emissions will be accelerated when economic growth occurs in an otherwise business as usual context. Another alternative scenario is possible with significant potential for deep decarbonisation of India’s coal-based electricity generation. The model structure was modified to create a scenario that assumes a radical shift towards advanced technologies with suitable gasifiers that work well with high-ash Indian coal.

The benefits from efficiency improvements are immense. According to IEA, energy efficiency gains since 2000 have prevented 6 percent of additional energy use and approximately 145 Mt equivalent of CO₂ emissions in 2017, and under its Efficient World Scenario predicts that energy demand growth could be potentially limited to just 82 percent between now and 2040, as opposed to the almost doubling of demand witnessed between 2000 and 2017 (IEA, 2018). Results from the simulation run presented in Figure 6.11, show that it is possible to flatten the curve of Indian CO₂ emissions from electricity generation well before 2050, possibly assisted by international capital investment and through measures assisted by an effective governance framework and suitable institutional capacity, explored in the next section.

![Accumulated CO₂ Emissions](image)

*Figure 6.11: Reduction in emission reduction with the integration of high-efficiency-low-emission coal plant with CCS*

Carbon emission reduction in coal-fired power plants presents a significant prospect for India’s coal future. Several readily deployable technologies, such as ultra-super-critical technologies as well as Integrated coal gasification combined cycle (IGCC) power plants, can offer significant emission reduction potential for coal power plants.
Results from modelled scenarios show that it may be possible to do more of everything (renewables, nuclear power, efficiency investment, and clean coal all together). Results clearly show that business as usual is not an option and coal cannot be ignored or dismissed when considering what might be done. And while switching to IGCC enabled with carbon capture plants is perhaps the only possible way to flatten CO\textsubscript{2} emissions from coal-powered generation in a timely manner, these may not be an economically feasible India will be willing to consider, without significant support, soon.

**Conclusions**

This chapter presents a simple system dynamics model to examine the possibility of reducing India’s CO\textsubscript{2} emissions by simply bringing about efficiency improvements and answer the question: *What will be the impact of India’s overlapping energy policy objectives on coal use for power generation and India’s carbon emissions pathways?* Key policies leverage points with significant future prospects for India’s power generation pathways were tested. The simulation results of the reference scenario suggest that India cannot reduce its carbon emissions within the scope of policies currently pursued. CO\textsubscript{2} emission reduction in India can only be realised with the deployment of clean coal technologies enabled with CCS. A clear milestone was seen in 2035 when the total emissions plateaued to 2005 levels. The model analysed the dynamics between renewable and coal-based capacities anchored around subsidies boost to supports India’s policy objectives.

Long-term investments that can effectively switch more coal-based capacity, a significant reduction in available subsidies and significant improvements in efficiency gains and demand-side management will all be crucial for India’s CO\textsubscript{2} reduction ambitions. The existing political realities and the pressures to keep costs low will, however, continue to militate in favour of coal power in its existing form in the near future.

Global energy governance arrangements and processes have a significant role to play to ensure foreign investment and investments in clean-coal technologies and improvements in energy efficiency that will be crucial for lowering, or even stabilizing India’s environmental footprint are made available. The model aids an aggregated analysis in its current form and takes into consideration only the net emission from coal-based electricity generation. Other carbon-intensive sources like transportation and agricultural emissions have not been considered, within the current context due to the specific nature of the problem being analysed.

The role of other cleaner sources, notably nuclear power, in helping diversify the future electricity generation mix of India and helping facilitate sustainable and green generation will also be crucial. In 2016, nuclear power’s share in electricity generation stood at 2.6 percent (38 TWh) (3 percent
according to NEP, 2015), while 75 percent (1105 TWh) of the total electricity generation came from coal. Despite indicated approvals in 2017 for ten 700 MWe PHWRs and a further ambition for two more reactors of 1000 MWe each, taking the total capacity to 22,480 MWe by 2030 (NEP, 2015), there have been wide speculations in the industry that the nuclear capacity (7 GWe in 2017) could only potentially reach 22.5 GWe in 2031, missing the 63GWe target as originally outlined in India’s 12th five-year plan (WNA, 2019). Despite a very low nuclear contribution at this stage, integration of nuclear in India bears the potential of substituting coal-based capacity if suitable conditions are created and proper planning is carried out. According to current expectations, the expansion of nuclear power on the timescales of interest to this research will be modest and for this reason, and because of a desire to seek simplicity in the modelling whenever possible, nuclear energy has been excluded from this analysis thus far. It is however noted that a higher growth rate for nuclear energy might be possible rendering its contribution as substantial. This we would commend if it can be achieved consistent with other major policy goals - most especially in the area of energy economics.
Chapter 7: The Future of Clean Coal in India

The contents of this chapter can be found in part or whole in the following peer-reviewed publications:
Madhavi, M. and Nuttall, W.J., 2019. The Future of Clean Coal in India, at The International Conference on Energy and Sustainable Futures (ICESF) 2019, Nottingham, UK

Overview

This chapter is set against the insights generated by the India coal model in the previous chapter. The India coal model showed that the adoption of efficiency improvement measures on its own will not succeed in capping CO_2 emissions to desired levels from India’s coal-dominated power generation. The importance of expanding power generation capacity to meet the growing energy demands of India’s growing population and changing demographics has also been highlighted and cannot be ignored. While renewable energy costs are falling and further reductions in them are predicted, there are formidable challenges associated with grid integration, storage and intermittency. Coal is expected to remain a significant part of India’s energy mix in the foreseeable future under the current policy climate. Until such time solutions to the challenges posed by renewable technologies are clearly worked out and a clear departure from the current pattern of generation is undertaken, India may have to consider a mix of large and small, central and distributed technologies to achieve both its domestic energy objectives as well as successfully meet the global climate goals.

The current policy structure is predominantly focused on expanding the generation capacity, which has resulted in plans to develop and deploy supercritical pulsed coal technologies. It is critical then that India promotes technologies that can allow coal-based power technologies to respond to future challenges in environmentally sustainable manner. Such policy choices, however, cannot be made without careful consideration of relevant factors; decisions about power plant technologies have the consequence of locking them in for a period of about 40-60 years. Studies, including the modelled scenarios presented in the previous chapter, suggest that highly advanced clean coal technologies present significantly improved prospects for India’s ambitions to minimise greenhouse gas emissions while maintaining some of the socio-economic benefits of using local coal.

A variety of factors will need closer examination to establish the techno-economic relevance and suitability of various clean coal technologies in a future Indian energy system to balance energy policy objectives. Not all clean coal technologies are created equal; some require higher coal quality while others are expensive and these may not be suitable in India’s context. A systematic and objective assessment of emerging technologies is required against the backdrop of India’s regulatory landscape to assess the suitability of relevant technologies in India’s socio-economic context. Such
an assessment is essential for any future reform in governance arrangements and process such that it can suitably address challenges posed by India’s emerging coal dynamics to global climate and sustainable development goals. This section seeks to contribute to such a planning process by assessing technology options in the Indian context, and presents recommendations towards developing a coal-power technology roadmap for India. An overview of the status of clean coal technology along with an assessment of issues relating to its consolidation and integration in India is presented. The balance of a possible future portfolio of coal-based generation technologies and their techno-economic feasibility in India is explored.

**Context**

India’s energy system is expected to undergo significant transformation in the coming years. With studies forecasting growth in all key macro-indicators (World Bank, 2015; International Energy Agency (IEA), 2015), growing population base (UN, 2017), rapid modernisation and expansion of the manufacturing sector, India’s energy demand growth is predicted to double to approximately 11% by 2040 (BP, 2019). And while India’s economy has been growing over the past decade, its per capita energy consumption remains low at the moment (India’s Human Development Index (HDI) is 0.586 and ranks 135 in the world), it is expected to increase significantly in the coming years.

Coal’s share in India’s primary energy mix has grown due to the expansion of India’s power generation fleet and increased use of coking coal for India’s industrial growth at the back of policies such as ‘Universal Electrification (Saubhagya)’ and ‘Make in India’ (IEA, 2015). Coal-based generation is expected to remain the main source of electricity generation in the country for many years to come, fuelling and supporting the targeted GDP growth envisioned by the government (CEA, 2018). To reduce its dependence on imported fuels India aims to rely on its sizeable coal reserves mined in many Indian states (ibid). Hard coal deposits in India spread over 27 major coalfields, mainly confined to eastern and south-central parts of the country, while 90 % of 36 billion tonnes lignite reserves occur in the southern State of Tamil Nadu (CIL, 2019). A cumulative total of 319.02 billion tonnes of coal have so far been estimated in the country by the Geological Survey of India (Ministry of Coal, 2019; CIL, 2018).

In the meantime, India’s CO₂ emissions have increased at a compound annual growth rate (CAGR) of 5 percent between 1990 to 2004. Solid fuels in India account for about 70 percent of India’s annual CO₂ emissions, and most of this comes from coal-based power plants. India, a signatory to the COP21 Agreement, has pledged to improve the emission intensity of its Gross Domestic Product (GDP) by 33 to 35 percent below 2005 levels and increase the share of non-fossil fuels to 40 percent by 2030 (INDC, 2015). The India-coal model developed in this PhD research, presented in previous
chapter, shows that India, with some policy push, can manage to meet its intended nationally determined contribution by lowering the carbon intensity of its economy. However, continued use of coal, without carbon capture and storage, will result in a total net increase in its CO$_2$ emissions reaching disastrous levels in 2050 (BP, 2019; Model Results). Given India’s development agenda, its infrastructure deficit and its NDC targets, there are significant challenges ahead of India, and as a result of this globally, that need to be seriously addressed to limit rising global temperatures to 1.5°C by 2050. The role of technological intervention in helping India balance its various energy policy objectives becomes invaluable. It is in this context that this chapter examines the technological and economic implications associated with the integration of clean coal technology integration in India and underlines options and recommendations for the future.

**Coal Power Sector in India: Background and Status Update**

Coal is the most abundant fossil fuel in India, accounting for more than half of the country’s energy needs. Indian hard coal reserves are spread over 27 major coalfields, scattered across many Indian states mostly in the eastern and south-central parts of the country. India also has sizeable lignite reserves, estimated at around 36 billion tonnes, deposited mainly in the southern Indian state of Tamil Nadu. Given coal’s abundance in India and its role in providing secure and affordable supplies of energy, coal dominates India’s energy matrix, accounting for 56 percent of the country’s total primary energy consumption, presented in Figure 7.1 (EIA, 2020).

**India total primary energy consumption by fuel type, 2019**

![Graph of India total primary energy consumption by fuel type, 2019](image-url)

*Figure 7.1: Primary Energy Consumption Matrix in India in 2017
Source: International Energy Agency, World Energy Outlook 2019 (Note: Total may not equal 100% because of independent rounding)*
The power sector is likely to remain one of the biggest consumers of coal as the expected growth in electricity projected in the immediate future will be based on coal. Figure 7.2 presents India's electricity generation profile in 2017 (BP, 2018).

![India's Electricity Generation(%)](image)

**Figure 7.2: Electricity generation from various sources in India 2017**
Source: Data from BP, 2018

**Historical drivers and power sector reform in India:** Coal-based electricity generation in India began in 1899, with the establishment of a 1 MW power station in Kolkata (then Calcutta) (Chikkatur, 2008). The earliest technologies in India were directly imported from Britain and were of the *stoker water-tube* kind. In these technologies, coal was completely burnt on a grate and the heat generated in the process was used to heat water/steam circulating in tubes encasing the boilers. The hot and pressurised steam was used to rotate the steam turbines. These turbines were, in turn, connected to an electromagnetic generator that produced electricity (Chikkatur & Sagar, 2007). These units ranged in size between 1-15 MW and used high-quality coal. The stoker-fired boilers continued to be used well into the 1960s for electricity generation in India. These were replaced by pulverised coal (PC) technology, invented in the 1920s in the United States (ibid). In PC technologies, the burning of coal on stoker grates was replaced by pulverisation of coal into a fine powder before adding them into pressurised air burners. By enabling more controlled combustion of coal resulting in more pressurised steam at higher temperatures and using larger boilers, PC technologies brought about significant improvements in the efficiency of steam turbine aided electricity generation. The process of coal-based electricity generation is shown in Figure 5.2 and described in Chapter 5.

**Power sector reform:** Electricity played a vital role in driving India’s post-independence development and reinstating domestic self-sufficiency. A series of structural reforms aimed at making electricity available in the most equitable manner to all sections of society were introduced over several decades post-independence. Several studies (Baijal (1999); Chikkatur & Sagar (2007); Chikkatur (2008); Tongia (2003)) provide a deeper contextual understanding and appreciation of various
factors that have, over the years, contributing to the evolution of the existing institutional framework in India shaping the power sector in the form as it currently exists. Chikkatur (2008) highlights that the private sector companies that existed at the time were deemed unsuitable for providing nationwide access to electricity, which was crucial for India’s social development, and thus the state machinery assumed total control upon all aspects related to the generation, transmission and distribution of electricity. This is believed by many scholars (Tongia, 2003) to have initiated the domination of the public sector on India’s power sector, which consolidated its stature over many decades and continues, even to this day, to dominate India’s power sector.

Key reforms were introduced in the early years of the millennium: The Electricity Supply Act of 1948, was substituted by the Electricity Act, 2000, which sought to consolidate the institutional structure to bring the generation and supply of electricity under the control of one authority; it led to the creation of The Central Electricity Authority (CEA) to develop, promote and assist efficient national power policies between various involved parties and stakeholders (CEA, 2018). The State Electricity Boards (SEBs), created under the Electricity Supply Act of 1948 as autonomous bodies were corporatised under the Electricity Act 2003, to be under the supervision of State governments to administer state grid systems and were to assume the responsibility of capacity addition (Chikkatur, 2009).

For many years, in the absence of indigenous manufacturing infrastructure, India’s power plants had to be imported (Chikkatur, 2008). Some of the earliest pulverised coal plants installed in 1952-53 were imported 57.5 MW units using assisted boilers and turbine-generators, while imported units ranging between 60-210 MW in size were installed in the 1960s and 1970s. These imported units consistently underperformed and encountered a range of operational issues as they were not designed for poor quality India coal; significant delays and heavy expenses were incurred on constant maintenance, repair and modifications (Baijal, 1999).

Recognising the need for a domestic power equipment industry, a holding company, Bharat Heavy Electricals Limited (BHEL) was incorporated in 1964 to manage and coordinate activities of:

- Heavy Electricals Limited (HEL) in Bhopal manufacturing steam and hydro turbo-generators;
- Heavy Power Equipment Limited (HPEL) in Hyderabad in Telangana for manufacturing steam turbo generators and high-pressure pumps and compressors; and,
- High-Pressure Boiler Plant (HPBP) in Tiruchirappalli (Tamil Nadu) for manufacturing high-pressure boilers (BHEL, 2019).
BHEL, by the mid-seventies, reportedly contributed 910 MW of power generating equipment to India’s capacity of 4,579 MW (ibid). Other centrally owned public sector companies, namely the National Thermal Power Corporation (NTPC), National Hydro Power Corporation (NHPC) and Nuclear Power Corporation of India Limited (NPCIL) etc., were also established in the 70s and the 80s to increase the capacity of underperforming state electricity boards. At this time, BHEL dominated the supply and manufacture of power plants in India. Based on the recommendations of an advisory subcommittee in 1980, the adoption of supercritical steam parameters was rejected in favour of 500 MW units until a further revision in 2000. As a consequence of this decision the country remained locked-in to use sub-critical technology and is only just beginning to adopt super-critical technology (Chikkatur & Sagar, 2007).

Coal-based usage and generation were further consolidated in the aftermath of the oil-shocks of the 1970s, and reliance on coal-based power plants continues to safeguard against price fluctuations and supply disruptions. In the period between 1970 and 1990, more than 200 coal power plants of 110-210 MW units were added to India’s fleet of power generators and the total coal-based capacity grew from 7.5 GW in 1970 to 43 GW in 1990-91 to 185 GW in 2016 (CEA, 2016). With the advent of the Electricity Act 2003, generation was de-licensed; today any entity could set up a power plant, if it satisfies the Technical Standards for Connectivity to the Grid, set out by the Central Electricity Authority.

A Power Exchange was also set up in 2008 in India, where any merchant power plant could sell power in one hourly blocks (revised to fifteen minutes blocks since 2011) (GoI, 2008). In a shortage condition at that time, many private sector entities were encouraged to set up merchant power plants to sell power in the power exchange; the contribution of the private sector continues to grow (CEA, 2018). Currently, most of the power plant units installed in India are manufactured indigenously. In 2017-2018, of the total installed generation capacity of 344 GW, coal’s share in the generation mix accounted for a staggering 56.2%, as shown in Table 7.1 below.

<table>
<thead>
<tr>
<th>Source: (CEA, 2019)</th>
<th>Table 7.1: India’s installed capacity in 2019 by source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed Capacity (in MW)</td>
<td>Share (in %)</td>
</tr>
<tr>
<td>Coal</td>
<td>203,154.5</td>
</tr>
<tr>
<td>Hydro</td>
<td>50,008.03</td>
</tr>
<tr>
<td>Wind</td>
<td>36,000.42</td>
</tr>
<tr>
<td>Solar Power</td>
<td>30,708.85</td>
</tr>
<tr>
<td>Biomass</td>
<td>9,271.3</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6,780</td>
</tr>
<tr>
<td>Gas</td>
<td>24,937.22</td>
</tr>
<tr>
<td>Diesel</td>
<td>509.71</td>
</tr>
<tr>
<td>Total</td>
<td>361,370.03</td>
</tr>
</tbody>
</table>
Coal-based generation remains to be the mainstay of electricity generation in India and is poised to fuel and support India’s energy growth in the foreseeable future (CEA, 2018). Much of India’s predicted increase in primary energy demand, both in absolute and per capita consumption terms, from 6 percent currently to 11 percent in 2040, requires increasing power consumption as more people move to urban settlements from rural areas and as India’s industrial output expands (IEA, 2015). India’s predicted macro-indicators for 2040 signalling a steep growth trajectory for the future are presented in Table 7.2 (INDC, 2015).

### Table 7.2: India’s projected macro-indicators

<table>
<thead>
<tr>
<th></th>
<th>India’s macro-indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>Population</td>
<td>1.2 billion</td>
</tr>
<tr>
<td>Population in Urban Areas</td>
<td>377 million</td>
</tr>
<tr>
<td>GDP (in trillion, 2011-2012 USD)</td>
<td>1.69</td>
</tr>
<tr>
<td>GDP per capita (nominal)</td>
<td>1408</td>
</tr>
<tr>
<td>Electricity demand (TWh)</td>
<td>776</td>
</tr>
</tbody>
</table>


Coal remains the dominant source of power generation in India, accounting for 80% (74% as per CEA figures) of output by 2040 (BP, 2019). There is every possibility that the contribution of other resources such as liquefied natural gas (LNG) and nuclear power in India’s electricity generation will improve in the future, but coal’s share is likely to remain comparatively much larger for many decades to come. As a result of this, while India’s carbon intensity of power grid declines by 29 percent at the back of efficiency improvements in power plants, and India may perhaps successfully manage to meets its intended nationally determined contributions (INDCs) as communicated to the United Nations Framework Convention on Climate Change (UNFCCC), its total net CO₂ emissions may, in fact, double to 5Gt by 2040, increasing India’s share of global emissions from 7 percent in 2018 to 14 percent by 2040 (BP, 2019). These figures are consistent with modelled results from coal model presented in the previous chapter.

Recognising the importance of coal-based generation in fuelling the targeted GDP and HDI growth in India, while simultaneously transiting to cleaner, inclusive, and sustainable energy pathways, several new measures focussed on improving the efficiency and environmental performance of coal-based generation have recently been announced by the government (CEA, 2018). Currently, however, 85 percent of Indian coal plants are based on subcritical boiler technology, which have been adapted to be used with Indian coal and in general terms perform poorly given their low conversion efficiency (IEA, 2015).
Results from the India coal model show that while the higher-efficiency supercritical pulverised coal technologies are significant for bringing about efficiency improvements, these do not reduce carbon emissions. Integration and use of advanced technologies for coal-based generation is projected to play a central role in helping India meet the challenges in the coal-power sector. Having established the significance of coal-based generation to India’s energy trilemma, the techno-economic suitability of various coal-based generation technologies specific to India’s context is assessed in the following section.

Techno-economic Feasibility Assessment of Coal-based Power Generation Technologies in India

A range of technological options that seek to improve the environmental performance of coal are grouped under the general termed Clean Coal Technologies (World Coal Institute, 2005). The report on Clean Coal Technology by WCI (2005) cautions that the choice of technology needs to be carefully made as different technologies tackle different environmental problems, depending on the type of coal and country’s level of economic development; some of these technologies can be prohibitively expensive.

Many of these technologies have been widely integrated into power generation systems across the world given the vast range of benefits offered by them. Some of these include, inter alia, coal cleaning (beneficiation), use of electrostatic precipitators (ESPs) and fabric-filters (FFs)- these help in reducing the levels of particulate emissions; flue gas desulphurisation (FGDs) can remove as much as 99 percent of SOx emissions, while selective catalytic reduction (SCRs) and selective non-catalytic reduction (SNCRs) can effectively reduce NOx emissions by 80-90 percent; CO2 emission reduction can be brought about by bringing about improvements in thermal efficiency of coal-fired power plants and adoption of advance zero-emission technologies (WCI, 2005). A detailed overview of various clean coal technologies is presented earlier in Table 5.4 (also (Madhavi & Nuttall, 2019)). For the specific purposes of the analysis in this section, a technological feasibility assessment of technologies that have the potential to significantly reduce CO2 emissions is presented.

While combustion-based technologies already dominate the technological landscape across the world, a range of advanced technologies have now been successfully developed and are getting deployed globally to address the environmental challenges facing coal-based generation. Studies, mainly those by World Bank (2008); CEA (2018); Chikkatur (2008); Chikkatur & Sagar (2007); Tongia (2003) suggest the relevance of both combustion and gasification-based coal power generation technologies for India in the long run. These studies have the advantage of being India-centric and remain, along with reports by India’s CEA and PowerMin, the main resource for this assessment.
A number of technology types were assessed, but because of challenges associated with the poor quality of domestic coal, only a limited number of technologies were found suitable for India. Technologies that would require better coal types not produced domestically in India were left out of this assessment, given India’s policy to reduce reliance on imported coal and their selection would, therefore, be counter-intuitive. Another important consideration guiding this selection was to consider such technologies that could be deployed to implement the policies that can bring about the reduction commensurate with the Reference Growth with Climate Action scenario in Chapter 6. Based on these primary considerations, the following technology groups were found relevant in India’s context:

1. Pulverised Coal Combustion and High-Efficiency Low-Emission (HELE) Coal Technologies;
2. Circulating fluidized bed combustion (CFB); and
3. Integrated gasification combined cycle (IGCC).

**Pulverised Coal Combustion and High-Efficiency Low Emission Coal Technologies:**

*Pulverised Coal Combustion Technologies*: As mentioned in earlier sections, to produce electricity through pulverised coal combustion systems, steam coal, or thermal coal, is finely milled or pulverised, to increase its surface area and to allow it to burn quickly. It is then blown into the combustion chamber or boilers at high temperatures, which converts water flowing through tubes lining the boiler into steam. This steam is then used to run the shaft of a turbine connected to a generator with coiled wires at one end where electricity is produced. Pulverised coal combustion (PC) is the most widely used technology in coal-fired power plants globally and can be categorised, based on differences in boiler temperature and pressure as follows:

1. **Subcritical Technology**
2. **Supercritical (SC) Technology**
3. **Ultra-supercritical (USC) Technology**

A subcritical boiler works below the steam-water critical point—the temperature of 374.15 °C and pressure of 218 atmospheres (221 bar or 225.6 kg/cm²), while supercritical boilers work above these parameters. The phase change diagram of water showing its various states or phases is shown in Figure 7.3. Detailed thermodynamic analysis of efficiency enhancement in power plants, is beyond the scope of this work, but can be seen in work by (Murugan & Subbarao, 2008).
Figure 7.3 Liquid-vapour critical point in a Pressure-Temperature phase diagram
Source: ("DifferenceBetween", 2018)

[Note: The critical point of a substance is the temperature and pressure at which it exists in an indistinguishable state. The commonly known phases solid, liquid and vapour are separated by phase boundaries, i.e. pressure-temperature combinations where two phases can coexist. At a critical temperature, Tcr and critical pressure Pcr the liquid-vapour boundary terminates and only one phase exists.]

Subcritical units are typically designed to achieve thermal efficiency of up to 38 percent (NITI-IEEJ, 2017). Moving to higher efficiency pulverised technologies can yield significant reductions in fuel requirements and in the volume of CO₂ emitted and therefore in the capture and storage requirements and can act as an essential steppingstone towards the deployment of carbon capture, use and storage technology (CCUS) (WCA, 2005). The essential distinguishing features between PC technologies have been listed in Table 7.3.

Table 7.3. Typical parameters and specifications of various PC Technologies

<table>
<thead>
<tr>
<th></th>
<th>Subcritical PC Plants</th>
<th>Supercritical PC Plants</th>
<th>Ultra-supercritical (USC) Plants</th>
<th>Advanced USC Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam outlet pressure¹ (MPa)</td>
<td>Below 22.1 MPa</td>
<td>22.1-24.7 MPa</td>
<td>22.1-27 MPa</td>
<td>Above 22.1 MPa</td>
</tr>
<tr>
<td>Steam outlet temperature¹</td>
<td>&lt;538 °C</td>
<td>565°C</td>
<td>565-625°C</td>
<td>Above 625-650°C</td>
</tr>
<tr>
<td>Net plant efficiency¹ (%)</td>
<td>35-38% (for India it is 29%)</td>
<td>39.1%</td>
<td>40.0-42.5%</td>
<td>42.5-46%</td>
</tr>
<tr>
<td>Capital cost ($/kW)¹</td>
<td>1300-1500 (600-1980)³</td>
<td>1350-1550 (700-2310)³</td>
<td>1400-1650 (800-2530)³</td>
<td>NA</td>
</tr>
<tr>
<td>CO₂ Intensity² (g CO₂/kWh)</td>
<td>≥ 880</td>
<td>800-880</td>
<td>740-800</td>
<td>670-740</td>
</tr>
<tr>
<td>Coal Consumption² (g/kWh)</td>
<td>≥380</td>
<td>340-380</td>
<td>320-340</td>
<td>290-320</td>
</tr>
</tbody>
</table>

Source: 1: (Tavoulareas, 2008); 2: (WCA, 2015); 3: (NITI-IEEJ, 2017)

High-efficiency low-emission (HELE) technologies: These are a group of technologies that have been designed to increase the efficiency of coal-fired power plants. An increase in efficiency in coal-based power plants can result in lower auxiliary and fuel consumption per unit of electricity produced, while simultaneously reducing CO₂ and other greenhouse emissions such as nitrogen oxide (NOₓ), sulphur dioxide (SO₂) and particulate matter (PM) (WCA, 2015). World Coal Association estimates that a one-percentage-point improvement in the efficiency of a conventional power plant can achieve a 2-3% reduction in CO₂ emissions.
At an estimated 3-percentage-points higher efficiency than subcritical plants, supercritical plants can, using supercritical steam parameters, bring about up to 45 percent increase in efficiency of pulverised combustion plants (Ghosh, 2005). This is due to elevated steam conditions – superheat and reheat steam temperatures and higher steam pressures, which allows for a more complete combustion of coal resulting in more electricity per unit of fuel heat input corresponding to higher efficiency gains and reduced CO₂ emissions. Replacing the existing subcritical technologies with SC and USC technologies have been estimated to potentially achieve higher efficiencies resulting in around 23 percent reduction in CO₂ emission per unit of electricity generated (Nalbandian, 2008). This presents promising potential and exciting prospects for a country like India, scrambling to balance policy priorities between attaining economic growth, energy security and prosperity for its citizens, it does not bring about emission reduction at levels needed for Net Zero objectives.

The comparatively cheaper High-Efficiency Low Emission coal technologies are of vital importance to Indian policymakers in the immediate future for bagging quick improvements in India’s coal-fired plants that currently have a net efficiency of 29 percent, much lower than the global average (Chikkatur & Sagar, 2007). Large-scale adoption of these technologies will, however, continue to see emission growth from coal-fired power over many decades.

*Current status of Pulverised Coal and HELE technologies in India:* In India, the standard for coal-power technologies have traditionally been the Bharat Heavy Electricals Limited (BHEL) 500 MW sub-critical pulverised coal units, supported by assisted boilers with the main steam-pressure of 170 kg/cm², the best of these units operating at a higher-than-average efficiency of 33 percent (Central Electricity Authority, 2003). Despite steady improvements in unit sizes and efficiencies, these BHEL-manufactured units fall behind a vast range of advanced, more efficient and cleaner technologies now available internationally. Efficiency improvements are critical considerations for future coal-based generation in India. According to an estimate by India’s Ministry of Power, the introduction of new ultra-supercritical (USC) technology can improve the efficiency of coal-based power generation in India by 1.5 percent over supercritical units (CEA, 2018).

In recent years, Indian’s Ministry of Power has reported that several 660/800MW Units are currently operational in the country and many more are under construction; improvements in the steam parameters of supercritical units from the initial design specification of 247 kg/cm², 537/565°C to 247 kg/cm², 565/593°C are also being undertaken (CEA, 2018: 77). CEA (2018:32) reports the following:
• The recently awarded plants of Khargone and Jawaharpur Super Thermal Power Plants (TPP) to be implemented with ultra-supercritical class steam-pressure specifications of 280 kg/cm² and temperature of 600°C

• Construction:
  o approved for eleven 660MW supercritical units (approved in September 2009);
  o approved for nine 800 MW supercritical units (approved in January 2011) by NTPC and DVC under the Phased Manufacturing Programme (PMP);
  o planned for coal-based Ultra Mega Power Projects (UMPPs) with a capacity of 4,000 MW each based on supercritical technology. The objective of UMPPs is to ensure cheaper tariffs; it can supply to various states with resource sharing and utilisation;

• Four of these units, namely Mudra in Gujarat, Sasan in Madhya Pradesh, Krishnapatnam in Andhra Pradesh and Tilaiya in Jharkhand are fully commissioned.

• The cost of electricity at these units is:
  o INR/kWh 2.264 (Mudra in Gujarat);
  o INR/kWh 1.196 (Sasan in Madhya Pradesh),
  o INR/kWh 2.333 (Krishnapatnam in Andhra Pradesh)
  o INR/kWh 1.77 (Tilaiya in Jharkhand)

(1 INR = USD 0.014)

According to the IEA (2018), the supercritical plants that have been commissioned in India in recent years account for around 15 percent of India’s total coal-powered fleet. Several announcements have been made in the recent year by India’s nodal agency, the CEA, indicating intentions to increase the share of higher-efficiency technologies to almost half of the total including some USC and integrated gasification combined-cycle (IGCCs).

All these indicate the robustness of simulated results from the India coal model and point out that if the plans outlined above are implemented, India will be able to fulfil its Paris ambition to increase the efficiency to 38% by 2040. This, if successful, can be truly deemed to be a novel feat, considering the high ash content of Indian coal, and considering the need to retrofit some of the existing units with pollution control measures.

While supercritical technologies offer a range of benefits as these are well commercialised and are better understood than other advanced technologies, other significant factors will limit their effectiveness over the long term in India.
Estimates suggest that while supercritical technologies, on their own, are generally only 3-5% more expensive than subcritical technologies right now (Chikkatur, 2008; Ghosh, 2005), the estimated costs will increase significantly when the cost of pollution control devices are included. Ghosh (2005) and Chikkatur (2008) estimate that in India adding Flue Gas Desulphurisation (FGD) systems to subcritical plant increases the cost by 24% and 32% for a supercritical unit, compared to a conventional subcritical unit. The thermal efficiency of a supercritical plant with FGD improves by 5% over the subcritical technology without FGD. The efficiency gains may, therefore, be outweighed by the substantial increase in cost.

Better post-combustion clean-up (through particulate emission control, flue-gas desulphurisation for reducing SOx, SCR, SCNRs and low NOx burners and other pollutant control technologies listed in Table 5.4) are needed alongside these supercritical technologies to improve the environmental performance of pulverised coal combustion technology. While HELE plants achieve a significant reduction in emissions, they do not, just on their own, meet the criterion required to saturate India’s emission growth.

Recently, a range of more advanced technology options that offer higher efficiencies and improved environmental performances than HELE technologies have been increasingly adopted for coal-based generation globally. These include Fluidised Bed Combustion (FBC) and Integrated Gasification and Combined Cycle (IGCC); both of fer improved overall performances over HELE technologies and proven suitable to work with Indian coal types (Chikkatur, 2008). These are extremely significant for India’s clean coal future and have been analysed in the following sections.

**Advanced Clean Coal Technologies**

**Circulating Fluidized Bed Combustion (CFBC):** Unlike pulverised coal, fluidised bed combustion does not require coal to be finely milled or pulverised, and can combust larger pieces of coal (Ghosh, 2005). Fluidised bed combustion score over PC technologies in terms of its lower cost, ability to use lower-grade coal and lower level of pollutants. FBC, however, results in a higher level of solid wastes compared to PC technologies. The fluidised bed designs can be of bubbling or circulating types. Atmospheric and pressurised variants of the design can also be found (WorldBank, 2008). This study only analyses the circulating fluidised bed (CFB) technology as it is the most used variant under this technology type, and works well with high-ash fuels, such as lignite and Indian coal types.

In fluidised bed combustion, coal is burnt in a bed (less than 2 percent of coal) of ash and limestone particles suspended in a stream of upwardly flowing air (WorldBank, 2008: 16). The pressure of the air is high enough to elutriate the fine particles out of the bed (Chikkatur, 2008). Upon combustion,
the coal particles decrease in size and are carried higher in the combustor when secondary air is introduced. During the process, reduced size coal particles along with some of the sorbents are carried out of the combustor, collected in a cyclone separator, and recycled to the lower portion of the combustor—thus increasing boiler efficiency by increasing coal’s residence time in the boiler (Ghosh, 2005: 10). Coal and limestone are fed continuously into the furnace and unspent material and by-products such as ash, calcium sulphate and limestone are removed. Steam is generated in tubes that are placed along the wall of combustion chambers and can be superheated in the tube bundles placed downstream of the particulate separator (ibid). The separator device at the furnace outlet collects the bed materials from the flue gas, which is then recycled back to the furnace (ibid). The recirculation in CFBCs results in carbon conversion efficiencies of over 98 percent, leaving only a small amount of unburned residual char. The SO₂ and NOₓ emissions in CFBC plants are significantly lower than PC plants. About 90-95% of the SO₂ chemically react with sorbents such as limestone and dolomite, while NOₓ emissions are reduced by controlling bed temperature (Chikkatur, 2008: 151).

**Status of CFBC technologies in India**: CFB combustion technologies are being deployed worldwide, both in OECD as well as in developing countries. CFB technologies up to 300 MW are commercially available and are currently operating in Australia, China, Czech Republic, Finland, France, Germany, India, Japan, Poland, Republic of Korea, Sweden, Thailand and the United States (WorldBank, 2008: 16). According to World Bank (2008), there are more than 36 CFB units of 2-40 MW sizes currently in operation in India representing 1,200 MW of installed capacity. In India, BHEL in collaboration with Germany’s Lurgis Lentjes Energietechnik GmbH (LLB) manufactured the first utility-scale CFB boiler, which was used in Surat Lignite Power Plant (Chikkatur, 2008). However, the use of subcritical steam cycles and lower-grade coal together with heat loss in the cyclone and by removal of ash and spent sorbent limit the thermal efficiency of CFBC units.

The availability of commercially deployable CFBC units in large unit sizes of 500 MW and upwards may improve its prospects in India soon. More recently, however, a 600-MW supercritical CFB power plant has been successfully demonstrated at the Baima power plant in China (Guangxi, et al., 2016). This facility boasts the world’s largest capacity CFB boiler with SC steam parameters.

The cost will be a determining factor. World Bank (2008) estimates that CFBC-based power plants cost the same as pulverised coal plants with FGD units, however, studies by Ghosh (2005) and Chikkatur (2008) estimate that CFBC-based power plants can be 8-10% lower than a PC system with FGD and Selective Catalytic Reduction. Considering a somewhat extensive adoption of supercritical technologies in India and announcements indicating the adoption of ultra-supercritical technology, it can be assumed that CFBC will perhaps be only used at a reduced scale for power generation in the
country. Currently, an expert group review of CFBC technology is being carried out by CEA for assessing its larger-scale deployment and adoption potential in the power sector (CEA, 2018).

**Integrated Gasification Combined Cycle**

In Integrated gasification combined cycle (IGCC) coal is not combusted directly, but a high-pressure gasifier is used to turn coal into pressurised synthesis gas (syngas). The syngas is cooled, cleaned and fired in a gas turbine (Tavoulareas, 2008; (WCI, 2003)). Power in an IGCC unit is produced from both the steam as well as the gas turbine generators.

IGCC plants offer several benefits over pulverised coal-fired plants (Maurstad, 2005). The impurities from the syngas are removed prior to the power generation. Pollutants such as sulphur can be converted into reusable by-products, resulting in lower emissions of SO₂, particulates, mercury and CO₂. With additional process equipment, a water-gas shift reaction (CO + H₂O ⇌ CO₂ + H₂) can increase gasification efficiency and reduce carbon monoxide emissions, by converting it to carbon dioxide, which can then be separated, compressed and stored through sequestration or utilised as a chemical in industries (Chikkatur, 2008). The process overview of a standard IGCC cycle is presented in Figure 7.3.

*Figure 7.3: The process overview of Integrated Gasification Combined Cycle (with CO₂ capture)*

Source: Adapted from (Maurstad, 2005)
IGCC plants are proven to significantly enhance power generation efficiency and environmental performance due to the combination with coal gasification and gas turbine combined cycle. The technology may also offer capabilities for ultra-low emission systems and be an important part of a future hydrogen economy (WCI, 2003). Additionally, IGCC also offers prospects for the development of coal-based chemical processing as an adjunct to electricity production (Ghosh, 2005:16).

A number of gasifier technologies have now been developed which make it possible for IGCC to be used with high-ash India coal. Key attributes of these gasifier technologies are listed in Table 7.4. The use of gasifiers is dictated by the ash properties of coal (Maurstad, 2005). Due to its high-ash properties, gasification of Indian coal requires fluidised bed and moving-bed gasifiers (which offer greater circulation and flexibility of fuel) over the standard slagging entrained-flow gasification (because of its high-ash and high-ash fusion temperature). Fluidised bed gasifiers concurrently perform several functions such as fluidisation, gasification, removal of sulphur by limestone injection offering a limited number of independent variables for the desired process optimisation and is, therefore, known to offer limited operating flexibility (ibid). These gasifiers are currently in the R&D stages (Chikkatur & Sagar, 2007).

<table>
<thead>
<tr>
<th>Syngas outlet temperature</th>
<th>Moving-bed gasifiers</th>
<th>Fluidised-bed gasifier</th>
<th>Entrained-flow gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidant (air or oxygen) demand</td>
<td>Low</td>
<td>Moderate</td>
<td>High (Mainly oxygen)</td>
</tr>
<tr>
<td>Ash conditions</td>
<td>Dry or slagging</td>
<td>Dry ash or agglomerating</td>
<td>Slagging</td>
</tr>
<tr>
<td>Size of coal feed</td>
<td>&lt;50 mm</td>
<td>&lt;6 mm</td>
<td>Fine dust (&lt;500 µm)</td>
</tr>
<tr>
<td>Major manufacturers</td>
<td>British Gas Sasol, Sasol, Lurgi</td>
<td>HT Winker, Foster Wheeler, KRW, MBEL, U-Gas, Mitsubishi, GE-Texaco, Shell, E-Gas, Conoco-Phillips</td>
<td></td>
</tr>
</tbody>
</table>

Source: Adapted from (Chikkatur & Sagar, 2007) and (Maurstad, 2005)

The performance of gasification systems is determined by the kind of gasification and the method used in clean-up systems. There are two common kinds: air-blown gasification and oxygen-blown gasification.

While the use of air over oxygen for gasification reduces the cost and energy in air separation plant for oxygen production, it dilutes the exit gas with nitrogen increasing the size and cost associated with the gas clean-up system. Gasification temperature control has a significant role in determining its efficiency as higher temperature are needed for lower quality coal. Studies estimate that air blown gasification systems have three percentage-points higher efficiency as compared to oxygen blown entrained flow gasifier with cold gas clean-up; it also has 4.5 percent higher CO₂ emissions due to calcinations of limestone in the gasifier (NRC, 1995). More research and further advancements in gasification-based power production systems are required across its various aspects.
components such as in the gas turbine firing temperature, hot gas clean-up of the fuel gas, co-production of both chemicals and electricity, improvements in gasifier designs, and integration of gasification with advanced cycles and fuel cells, and it is estimated that with advanced systems the efficiency of IGCC based power systems can increase over 50 percent (NCC, 2003).

Notwithstanding the fact that coal based IGCC technologies are not fully commercialised and are significantly more expensive than the conventional PC technologies (Maurstad, 2005), and its future prospects will partly be dictated by cost reduction and changes in environmental policies globally the benefits of IGCC in India’s context cannot be side-stepped.

IGCC offers favourable conditions for CO$_2$ sequestration and possibilities for efficiency improvements exceeding 50 percent by the production of hydrogen and the combination of IGCC with fuel cell technology (Ghosh, 2005).

- Prospects for the integration of Hydrogen-economy:
  - Besides offering increased efficiency in power generation, the production of hydrogen using IGCC technologies can be fundamental to creating a hydrogen economy in the country.
  - Hydrogen plays an essential role in low carbon transportation and will be invaluable for the decarbonisation of transportation sector and elimination of tailpipe emission from vehicles (Bakenne, et al., 2016).
  - The focus on hydrogen as a replacement fuel source for hydrocarbons is becoming increasingly popular worldwide as the idea of hydrogen economy gains popularity.
  - The use of coal to produce hydrogen for the transportation sector can bring about significant reduction in total energy use by the transport sector while helping create jobs through the creation of a domestic industry.
  - Using hydrogen in efficient fuel cell vehicles can result in nearly eliminating emissions from the transportation sector (USDOE, 2019).

IGCC development is considered to play a critical part in the longer-term strategic plan to develop a stable energy supply based on indigenous resources, which is being explored in many countries such as the United States and Japan. This creates opportunities for technology transfer and knowledge sharing (Ghosh, 2005: 16).

**Conclusion**

Environmental benefits of IGCC technology by far exceeds all other coal-based power generation technologies (World Bank, 2008; Ghosh, 2005). The most attractive feature of IGCC, in terms of its
environmental performance, is its ability to separate CO₂ from the flue gas stream assisting sequestration objectives (ibid). Due to the higher concentration of CO₂ in the flue gas stream, its removal is much easier and less expensive compared to conventional PC plants. Studies carried out in the United States (NCC, 2003) have shown that IGCC demonstration plants have can achieve electrical efficiencies closer to 40%. Improved efficiencies are expected with improvements in gasification technology.

A successful large-scale demonstration of the technical, environmental and economic performance of the IGCC technology will be an essential prerequisite to its wider adoption. There is, therefore, an urgent need for scaling-up the pilot plant to 500, 660 or 800 MW capacities. At present, despite over three decades of relevant R&D and demonstration experience worldwide, providing a rich insight into various technical and economic aspects associated with the technology, the IGCC technology is less mature than supercritical and ultra-supercritical pulverised coal technology (Chikkatur, 2007).

The capital costs for IGCC are also significantly higher globally compared to pulverised coal technologies. Prospects of IGCC in India will be dictated not just by larger-scale demonstration but critically by cost reductions. Varying cost estimates associated with IGCC exist. An MIT (2007) study estimates that the total plant cost (in $/kWe) could increase from 1,330 (2,140 with capture) for supercritical technology to 1,430 (1,890 with capture). The estimates of capital cost (in $/kW) published by the United States Department of Energy are 1,548 for subcritical technology, 1,574 for supercritical technology and 1,841 for IGCC plants, showing that a shift from subcritical technology to supercritical technology would increase the cost by less than 2%, whereas switching from supercritical plant to IGCC plant increases the costs by roughly 17%. Studies also indicate that within the IGCC technology there could be significant variation in cost based on specific attributes, for example, capture of CO₂ is likely to raise the cost of IGCC by 15 percent, while reducing efficiency by 6 percent (Holt, et al., 2003). Cost is also seen to vary based on technology manufacturer. A comparison between cost of electricity using various IGCC technologies is presented in Table 7.5.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Without Capture</th>
<th>With Capture</th>
<th>Increase in COE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texaco Quench</td>
<td>Cost ($/kW)</td>
<td>1270</td>
<td>1620</td>
</tr>
<tr>
<td></td>
<td>Heat Rate (BTU/kWh)</td>
<td>9300</td>
<td>1130</td>
</tr>
<tr>
<td></td>
<td>COE ($/MWh)</td>
<td>46</td>
<td>57</td>
</tr>
<tr>
<td>E Gas</td>
<td>Cost ($/kW)</td>
<td>1300</td>
<td>1850</td>
</tr>
<tr>
<td></td>
<td>Heat Rate (BTU/kWh)</td>
<td>8550</td>
<td>11000</td>
</tr>
<tr>
<td></td>
<td>COE ($/MWh)</td>
<td>46</td>
<td>62</td>
</tr>
<tr>
<td>Shell</td>
<td>Cost ($/kW)</td>
<td>1470</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>Heat Rate (BTU/kWh)</td>
<td>8370</td>
<td>10350</td>
</tr>
<tr>
<td></td>
<td>COE ($/MWh)</td>
<td>49</td>
<td>65</td>
</tr>
</tbody>
</table>

Source: (Holt, et al., 2003)
India has been doing research on IGCC technology since the 1970s, culminating in a 6.2 MW plant developed by Bharat Heavy Electricals Limited (BHEL) in Trichy, India using fluidised bed gasification technology (Shackley & Verma, 2008). Scaling up BHEL’s existing pilot plant in India to a 125 MW demonstration project may require a funding in the upwards of approximately $100 million (Shackley & Verma, 2008).

In comparison, a standard PC plant would cost only half as much as an IGCC demonstration plant (Chikkatur & Sagar, 2007). For now, therefore, there seems to be little progress on IGCC. This is also clearly visible in policy documents and CEA’s annual reports. While a clear roadmap signalling clear intentions for bringing about improvements in pulverised coal-combustion has been charted by the government, little clarity has been offered on the way forward on the prospects for IGCC, which are highly relevant for emission reduction in India’s context.

IGCC can offer several benefits in India’s context, including increased efficiency from combined cycle, reduced resource consumption, lower cost of pollution-control technologies, greater ease of carbon capture, reduction in carbon emissions. IGCC systems can be effective in removing 95-99 percent of NOx and SOx emissions, while the syngas produced can be cleaned and burned to produce steam for a successive steam power cycle to produce electricity. All these together present great prospects, technologically, for low-quality domestic coal in India (WCI, 2005).

Meanwhile, there are studies that suggest that the level and timing of a so-called carbon charge, in the form of tax, cess, penalty or any other mechanism that disincentivises and constrains carbon emission will be crucial in signalling the transition in favour of near-zero emission technologies, making them economic and a favoured policy option (MIT, 2007). But these disincentives impact the welfare of global poor, locking them into a certain future of energy poverty and destitution. It is therefore important to carefully consider the choice of policy instruments and pathways.

Global Energy Governance institutions, frameworks and processes have a crucial role to play in facilitating closer collaboration with international counterparts, promote joint research and development and in effectively aiding the transition of Indian power systems from the current mix of sub-critical super-critical technologies to IGCC based power system in a timely and cost-effective manner. Carefully crafted processes or frameworks will, however, be needed that have the legitimacy and institutional capability to lead this transition. In the absence of such processes and forward-looking plan, the transition from sub-critical to supercritical power plant technology will continue to remain the preferred option in India given their shorter lead times, comparative cost advantage and their technological maturity; India will continue to be heralded for its successful
efforts for bringing about efficiency improvements for its power generation systems; for its herculean efforts for providing electricity access to millions of people, mostly in Indian villages (Ghosh, 2005; Chikkatur, 2007). These technologies, while suited for conditions today, will, however, not remain optimum under future conditions, particularly in a world where achieving NetZero objectives is becoming a mandatory prerequisite (MIT, 2007).

The technological feasibility assessment undertaken shows that varying degrees of reduction in CO$_2$ emissions can be achieved based on the choice of technology in India. For example, coal upgrading mechanisms such as coal washing and briquetting can result in 5 percent reduction; up to 22 percent reduction in CO$_2$ emissions can be brought about by improving the thermal efficiency by implementing higher class steam specifications in coal power plants; up to 25-50 percent reduction is possible by implementing advanced technologies such as integrated gasification combined cycle (IGCC) technologies; attention must also be paid to carbon capture and storage in India (WCI, 2005). CO$_2$ capture and storage can result in an almost 99 percent reduction in CO$_2$ emissions. These are, therefore, referred to as zero-emission technologies, without which any real future of coal is hard to imagine (ibid). CCS will be key for mitigating India’s energy security risks and global climate change risks, and will be a critical factor in determining coal’s future in a carbon constrained world and its implications for India must, therefore, be evaluated closely.

**CO$_2$ Capture and Storage in India**

While the adoption of supercritical and ultra-supercritical technologies offers some benefits for improvements in the overall efficiency of India’s coal-fired power plants, an essential part of the solution for reducing India’s rapidly increasing CO$_2$ emissions lies in the implementation of carbon capture, utilisation and sequestration technologies (CCUS) (Mukherjee, 2019).

These technologies allow the emissions of carbon dioxide from the exhaust stream of coal combustion, or gasification, to be removed, compressed, used or stored in a way that they do not enter the atmosphere. The stripped CO$_2$ must then be transported by pipelines or ships to be stored by injecting into the earth’s subsurface in depleted oil and gas fields or in deep saline aquifers depending on the specific (CCSA, 2019). A total storage capacity of 126 Gigatonnes (Gt) of CO2 in depleted oil fields, 800 Gt in depleted natural gas reservoirs and an estimated 400-10,000 Gt in deep saline formations has been estimated (WCI, 2005). The stored CO$_2$ can also be economically beneficial and used to boost the production of oil and coalbed methane through techniques referred to as enhanced oil recovery (EOR) and enhanced coalbed methane recovery (ECBM) (ibid).
India’s total net CO₂ emissions, as also mentioned earlier, has been increasing steadily at a compound annual growth rate of 5 percent from 1990 to 2004 (Boden, et al., 2011). It is expected to roughly double to 5Gt by 2040, meaning India’s share of global emissions increases from 7% today to 14% by 2040 (BP, 2019). The existing fleet of coal-fired plants are the biggest point source responsible for roughly 70 percent of India’s CO₂ emissions (CEA, 2018). CO₂ capture at coal-fired power plants can offer a potentially effective way of reducing India’s emissions. Besides, these large coal power plants, representing the largest single point sources of CO₂ emissions, are likely to be targeted for attention in any carbon related legislation (Ghosh, 2005).

CCS process consists of three broad steps, namely, capture, transportation and storage of CO₂, which are described as follows (Akash, et al., 2016):

- **Separation of CO₂ from flue gas stream:** This can be done through post-combustion capture technologies (by retrofitting an existing plant with carbon capture units), pre-combustion technology (such as IGCC) and oxy-fuel combustion technology.
  - Post-combustion technologies use either absorption, where CO₂ is absorbed over a solvent such as mono-ethanolamine (MEA) or ammonia and exposed to higher temperature to separate CO₂, or adsorption using a membrane-based separator.
  - In pre-combustion technologies, such as IGCC, coal is partially oxidised with steam and air or oxygen to produce syngas, which is converted to CO₂ and H₂ by water-gas shift reaction and gas streams of CO₂ are separated for further use of storage.
  - In oxy-fuel systems coal is combusted in the presence of pure oxygen in upstream air separation unit (ASU), instead of air, to produce a flue gas steam containing CO₂ and water vapour.

- **Cooling and storage of CO₂:** The flue gas stream is then cooled and compressed to remove the water vapour and treated for the removal of other pollutants and any other gases and transported for utilisation or storage.

The readiness level of CCS technology in India is currently low, but there is evidence to suggest that research in the area has gathered some impetus in the recent years. Several studies (Akash, et al., 2016) (Chikkatur, 2008), (Chikkatur & Sagar, 2007), (Mukherjee, 2019), (Shackley & Verma, 2008) (Singh & Rao, 2014) (Singh & Rao, 2016) (Garg & Shukla, 2009) analysing the impact of carbon capture in coal-fired power plants in India exist, which provide a broad assessment of technical and cost implications associated with the technology. These studies indicate that retrofitting CO₂ capture in sub-critical plant may not be suitable. Given an estimated 30 percent loss in efficiency because of significantly higher auxiliary power consumption (rising by almost 24-30 percent), cost of generation
and coal use, retrofitting in existing sub-critical coal-fired plants currently incurs very high penalties by the government. Higher costs, reduced power and lower efficiencies in sub-critical critical plant, indicate that post-combustion carbon capture can only be viable in supercritical and ultra-supercritical. Other studies have further established that the cost of retrofitting an IGCC plant, originally designed without CCS may be cheaper than a supercritical plant in the longer run, and IGCC can potentially become competitive in the future with its supercritical counterpart based on the timing and level of a suitable carbon charge (MIT, 2007).

**CCS Potential in India**

Assessing the storage potential of captured and compressed CO₂ in India is equally critical to analysing the potential and viability of CO₂ capture technology in Indian context. Studies (Gale, 2008; Garg and Shukla, 2009; Holloway, et al., 2009; Shackley and Verma, 2008; Singh & Rao, 2014; Viebahn, et al., 2014) indicate that Indian sub-continent can be divided geologically into: *peninsular shield-largely composed of metamorphosised crystalline rocks; the Indo-Gangetic plains-built up of sands, clay and debris; and, extra peninsular region* (Garg & Shukla, 2009, pp. 1034-1035). It is estimated that the main potential of CO₂ storage sites could be located in the sedimentary basin along India’s peninsular margin both in the off-shore basin as well as in the states of Rajasthan, Gujarat, Assam, Cachar, Tripura and Mizoram (ibid).

A study conducted by the British Geological Society on behalf of IEA GHG R&D Programme (IEA GHG) assessed the geological storage potential in Indian deep saline aquifers, depleted oil and gas fields and deep unmineable coal fields to assess the suitability of CCS operation in India. Studies estimated the following theoretical storage potential (Gale, 2008, pp. 1-8; Garg & Shukla, 2009):

- 345 Mt in deep coal seams below 300 m across the country;
- Depleted oil and gas field of Assam, Assam-Arakan Fold Belt, the Krishna-Godavari and Cauvery basins, in the Mumbai-Cambay-Barmar-Jaisalmer basin area;
- Deep saline aquifers around India’s coastline and peninsula margin, particularly along the shallow off-shore areas in Gujarat, Rajasthan, Assam (located approximately 750-1000 Km away from five point sources emitting more than 5 Mt emissions per year);
- Basalt formation of the Deccan Traps and the Rajmahal Traps;
- Gangetic, Krishna-Godavari and Cauvery basins;
- Cambay basin and along the down dip to the east of Rajmahal coalfields;
- Gondwana basins;
- Saline aquifers of Assam, Cachar, Tripura and Mizoram;
These studies estimate the combined total geological storage potential of India to be around 572 Billion tonnes (Bt), of which basalt formations can accommodate about 200 Bt of CO₂; 360 Bt can be stored in deep saline aquifers; 5 BT in unmineable coal seams, and up to 3.7-4.6 Bt of CO₂ can be stored in the depleted oil and gas fields (Gale, 2008, pp. 1-8; Garg & Shukla, 2009). While these estimates indicate the need for considering new sites for power plants in relatively closer proximity to sites suitable for carbon capture. A map of potential geological CO₂ storage sites, large industrial clusters and coal mining areas in India are presented in Figure 7.4.

![Figure 7.4: Location of Coal Mines and CO₂ Storage Potential in India](image)

*Source: Inspired by (Holloway, et al., 2009); (Gale, 2008) and (Garg & Shukla, 2009)*

The preceding sections establish that a future low-carbon scenario will need a system-wide implementation of CCS technology. A large-scale demonstration and cost-reduction of all the clean-
coal technologies is an essential prerequisite to its adoption as a policy option for a developing country like India. As shown by the MIT study, a future price on CO₂ emissions may be instrumental in signalling a world-wide transition towards cleaner, low, or even, zero-carbon technologies which become cost competitive with the less efficient technologies with the inclusion of CO₂ emission price (2007).

Cost of carbon capture increases the cost of electricity and will determine the choice of technology for India. Some studies estimate that without CO₂ capture, the cost of electricity from IGCC will be only 5-10% higher than from supercritical plants. However, when CO₂ capture costs are considered the cost of electricity produced by IGCC would increase by 30-50 percent over that of supercritical plant without capture, or 25-40 percent over that of IGCC plants without capture. For supercritical plants with CO₂ capture, the cost of electricity increases by 60-85% over similar units without capture (ibid: 36).

Some variation in cost estimates across several studies can be seen, some estimates suggest that the costs of CO₂ capture and sequestration from new IGCC plants may increase the cost of electricity by 40-50% and with new PC plants these cost additions could even be around 80-90% (Holt, et al., 2003). Therefore, assuming, technical issues concerning CO₂ capture and sequestration are addressed globally and it is established to be effective, the steep increase in cost of electricity driven by integration of CO₂ capture technologies may prevent its large-scale adoption in a country like India, where even the slightest increase in costs can initiate significant discomfort in its social, political and economic landscape.

The studies, alluded to earlier, somewhat unanimously establish that successful implementation of CCS will unavoidably increase the cost of power generation in all the possible scenarios. While CCS adoption may be inevitable in the long-term future, in the foreseeable future and unless there is a much wider global demonstration and implementation of CCS technology at a larger scale, or a significant change in environmental legislation, the policy focus in India is likely to be aimed at achieving reduced emissions through improvements in thermal efficiency of PC plants, while considering pilot-scale implementation of some IGCC plants. Significant policy efforts directed towards accelerating the development, demonstration, and deployment of pollution control technologies in the country may be needed with some urgency.

The analysis of technological feasibility of advanced coal technologies presents significantly improved and encouraging prospects for its future integration in India’s generation system. However, given the importance of maintaining affordability of electricity for a vast majority of
Indians living at income levels of less than $1.9 per day (2011 PPP), the importance of assessing the economic feasibility associated with an intended transition can hardly be overstated. The economic assessment of coal-based generation technologies that are either already available or are likely to be technologically viable in the short-term future are evaluated in the presence of uncertainties in various parameters linked to anticipated changes in policy signals, regulatory framework and/or market condition and presented in the next section.

**Economic Assessment of India’s Clean Coal Technologies under Uncertainties**

The economic viability of various coal-fired technologies is assessed in this section. The generating technologies are compared in terms of the cost of electricity produced by each. A wide range of variables can have a significant impact on power generated from coal in India, and it is, therefore, important to recognise and explicitly take these into account while analysing any significant policy shift in the future (Chikkatur, 2007; Ghosh, 2005; Holt et al., 2003; World Bank, 2007). It is noteworthy that different power plants in India produce electricity at different costs, based on their location, age, operating conditions and efficiency parameters (Chikkatur, 2007). While a generalised assumption should be avoided in practice, it does provide a range to base assumption on. For this reason, the cost of electricity is calculated for 500 MW, 600 MW, 800 MW and IGCC units. Older units produce cheaper electricity than newly constructed units given amortisation of fixed costs but, at the same time, incur higher O&M costs given constant need for repairs and maintenance. Older units below 500MW have not been explicitly considered in the present research considering the recent decisions and announcement favouring larger units and planned retirement of most of the older units within the next decade (CEA, 2003).

**Monte Carlo Simulation:** A Monte Carlo simulation is integrated into the electricity generation costs for various units based on tariff guidelines issued by the Central Electricity Regulatory Commission responsible for electricity tariff regulation and pricing in India (CERC, 2019). The Monte Carlo simulation uses distribution of uncertain inputs and generates a range of possible outcomes and probabilities, or frequency of their occurrence in the future, and serves as a powerful tool for probabilistically characterising the risks of implementing a project on the chosen variable (Koc, et al., 2012). Monte Carlo simulations can help to analyse risks in future project by building model of possible results by assigning a probability distribution to every factor that carries inherent uncertainty over a prescribed number of iterations, allocating a different set of values in each run from within the uncertainty range specified to them (Palisade, 2019). The method applies extremely well to this enquiry. The @risk trial software was used for carrying out the simulations conducted in this section.
As previously mentioned, it is important for decision-makers to ensure that electricity remains affordable for all sections of Indian society. Technologies that increase the cost of electricity in India are unlikely to be considered as a viable option for many years to come (Chikkatur, 2008). Therefore, by comparing the cost of electricity produced by various power plants, their future economic feasibility of adoption can be assessed.

The cost of electricity from the selected plants are calculated based on guidelines specified by Central Electricity Regulatory Commission (CERC) in 2019, which is expected to remain valid for a period of the next five years up to 2024, when revised guidelines for a future period will be issued (CERC, 2019). While previous studies (Chikkatur, 2007; 2008; Ghosh, 2005; MIT, 2007; World Bank, 2008; Shackley and Verma, 2008) have estimated economic viability of various coal-based power generation technologies, analyses based on these new set of guidelines have not been found, and this research will be one of the first few studies basing the findings on these new guidelines.

According to CERC tariff regulation, the tariff for supply of electricity from a thermal generating station must comprise of capacity charge (for recovery of annual fixed cost) and energy charge (for recovery of all costs associated with primary and secondary fuel and any other reagent). The annual fixed cost (AFC) used for determining capacity charges, must, in turn, include return on equity, interest on loan capital, depreciation, interest on working capital, operation and maintenance (O&M) expenses. The normative parameters used in the calculation have been listed in Table 7.6.

Table 7.6: Parameters for determination of electricity cost for FY 2019-24 (CERC, 2019)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Cost Component</th>
<th>Normative parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Plant Capacity</td>
<td>500 MW/600MW/800MW</td>
</tr>
<tr>
<td>2.</td>
<td>Capital Cost</td>
<td>3484.12 Cr (@6.968 Rr Crore/MW)(^7)</td>
</tr>
<tr>
<td>3.</td>
<td>Debt-Equity Ration</td>
<td>70:30</td>
</tr>
<tr>
<td>4.</td>
<td>Return on Equity</td>
<td>15.5%</td>
</tr>
<tr>
<td>5.</td>
<td>Interest on Loan</td>
<td>200.28 Cr</td>
</tr>
<tr>
<td>6.</td>
<td>Working capital</td>
<td>439.53 Cr</td>
</tr>
<tr>
<td>7.</td>
<td>Interest on Working Capital</td>
<td>12.8%</td>
</tr>
<tr>
<td>8.</td>
<td>Depreciation Rate</td>
<td>4.92% of Capital Cost = 171.42</td>
</tr>
<tr>
<td>9.</td>
<td>Operation and Maintenance Cost (@28.7 lakhs/MW/Yr)</td>
<td>28.7<em>500 = 143.5 Cr (For 600 MW plant = 20.26</em>600 = 121.56 Cr; For 800 MW Plant = 18.23*800 = 145.84)</td>
</tr>
<tr>
<td>10.</td>
<td>Plant Load Factor</td>
<td>80%</td>
</tr>
<tr>
<td>11.</td>
<td>Plant Availability Factor</td>
<td>85%</td>
</tr>
<tr>
<td>12.</td>
<td>Useful life of generating station</td>
<td>25 years</td>
</tr>
<tr>
<td>13.</td>
<td>Escalation Rate for Domestic Coal</td>
<td>2% per year</td>
</tr>
<tr>
<td>14.</td>
<td>Specific Oil Consumption</td>
<td>0.5 ml/kWh</td>
</tr>
<tr>
<td>15.</td>
<td>Gross Calorific Value of oil</td>
<td>10000 kcal/L</td>
</tr>
<tr>
<td>16.</td>
<td>Cost of oil</td>
<td>35.831 Rs/L</td>
</tr>
<tr>
<td>17.</td>
<td>Gross Calorific Value of coal</td>
<td>3800 kcal/kg</td>
</tr>
<tr>
<td>18.</td>
<td>Cost of coal</td>
<td>3489.63</td>
</tr>
<tr>
<td>19.</td>
<td>Auxiliary Energy Consumption</td>
<td>8.5%</td>
</tr>
<tr>
<td>20.</td>
<td>Gross station heat rate (GSHR)</td>
<td>2350 Kcal/kg</td>
</tr>
</tbody>
</table>

\(^7\) 1 Cr = 10 million; 1 Indian Rupee (INR)=0.014USD; PPP Exchange Rate: 68.51*0.275 = 18.84INR/$ (World Bank) (on 25th October 2019)
As indicated earlier, given the sensitivity of electricity cost to parameter variables, it is important to account for uncertainty in key parameters while evaluating the value of future transitions, and can be done by integrating a Monte Carlo simulation in the electricity generation cost model (Koc, et al., 2012). The most important uncertain parameters that are likely to impact the cost of electricity are listed in Table 7.7.

<table>
<thead>
<tr>
<th>Uncertain Parameters</th>
<th>Minimum Value</th>
<th>Expected Value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost (Rr Crore/MW)</td>
<td>6.968</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Operation and maintenance cost for thermal power plants for FY 2019 -24 (in Rs Lakh/MW)</td>
<td>18.23</td>
<td>28.71</td>
<td>45.5</td>
</tr>
<tr>
<td>Depreciation Rate (%)</td>
<td>4.92</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Price of Coal</td>
<td>3200</td>
<td>4000</td>
<td>4500</td>
</tr>
<tr>
<td>Plant Load Factor</td>
<td>75%</td>
<td>85%</td>
<td>90%</td>
</tr>
</tbody>
</table>

It should be pointed out that the exact cost estimates for various key parameters needed to calculate the cost of electricity generated from an IGCC for India have not yet been published by the CERC. Studies elsewhere estimate that the cost associated with IGCC is likely to be over 30% higher than supercritical plants, and around 50% higher with built-in carbon capture units (Chikkatur, 2007; Ghosh, 2005; Holt et al., 2003; WorldBank, 2007). However, there are indications that these costs could be even higher. The calculated values of the cost of generation of electricity (in Rs/kWh) from various coal-fired power stations are listed in Table 7.8.

<table>
<thead>
<tr>
<th>500 MW PC unit</th>
<th>600 MW PC unit</th>
<th>800 MW PC unit</th>
<th>500 MW IGCC unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated cost of electricity (COE) (Rs/unit)</td>
<td>4.92</td>
<td>6.15</td>
<td>4.69</td>
</tr>
<tr>
<td>Total increment in cost with CCS (Rao &amp; Kumar, 2014)</td>
<td>NA</td>
<td>2.45</td>
<td>NA</td>
</tr>
<tr>
<td>COE with CCS in 2030 (Rs/unit)</td>
<td>8.6</td>
<td>8.56</td>
<td>7.95</td>
</tr>
<tr>
<td>% increase in COE with CCS</td>
<td>40%</td>
<td>41%</td>
<td>43%</td>
</tr>
<tr>
<td>Net plant efficiency (assumed based on studies)</td>
<td>35%</td>
<td>40%</td>
<td>45%</td>
</tr>
<tr>
<td>CO₂ emissions rate without capture (kgCO₂/kWh)</td>
<td>0.811</td>
<td>0.736</td>
<td>0.736</td>
</tr>
<tr>
<td>CO₂ emissions rate with capture (kgCO₂/kWh)</td>
<td>0.145</td>
<td>0.092</td>
<td>0.092</td>
</tr>
<tr>
<td>% CO₂ reduction per kWh</td>
<td>82%</td>
<td>88%</td>
<td>88%</td>
</tr>
</tbody>
</table>

8 CCS is not expected to be applied in India before 2030 (Viebahn, et al., 2014).
9 It is not entirely clear that the new IGCC units will not be enabled with carbon capture. But other studies seem to indicate that there may be a further increase in COE if IGCC units are not capture ready in India. An increase of Rs3.5/kWh is assumed in this study (37%-average of 20-55% increase estimated by IPCC (2005)).
Calculations indicate that the cost of electricity produced by using IGCC technologies is significantly higher than the cost of electricity generated using supercritical generation units. Even though there is less clarity on the specific timelines for the integration of CCS technologies in India’s coal-based generation today, this may be a necessary requirement in the future, and, therefore, for future estimates of the cost of electricity, the increase in cost with CCS is also indicated.

The single-point projection value of the cost of electricity generated with supercritical technologies is found to be much cheaper than with IGCC. Looking at the relative economic performance of the 500 MW, 600 MW, 800 MW and 500 MW IGCC plants (capture enabled units) it is observed that they compete very closely. The difference in cost between PC and IGCC plants widens if there is a further requirement to retrofit capture units in IGCC plants, however, IGCC technologies can be significant in reducing CO₂ emissions, as shown in Figure 7.5. Based solely on economic performance, single-point calculations favour post-combustion capture technologies over IGCC.

![Figure 7.5 Graph of Cost of Electricity against % reduction in CO2 emissions](image)

Monte Carlo simulations performed to analyse the impact of risk associated with the use of various coal generation technologies on the cost of electricity furnish key insights into the range of possible values for COE and the probability of their occurrence against each scenario (or technology choice). The COE distribution profile for coal-based generation for 500 MW, 600 MW, 800 MW and 500MW IGCC units are shown in Figure 7.6.

According to the COE distribution profile, in a 500 MW unit, the chances of the cost being between Rs 5.13-6.79 per unit was 90 percent. Most of the coal plants in the country today falls under this category, and currently, one unit of electricity roughly costs INR 6 per unit (but can vary between Rs 5.13-6.79).
However, investments in 600 and 800 MW supercritical units can return significant rewards and there is around a 90% chance that the cost of electricity will be competitive or lower than electricity generated using a 500 MW unit. IGCC technologies, however, significantly increase the cost of electricity, and the chances of electricity cost staying below Rs 8.5 per unit is less than 5 percent. Based simply on these narrow economic considerations, investment in IGCC does not appear economically viable until the time that annual fixed costs associated with these are significantly lowered.

This signals an urgent need for more research and development in the area. The need for larger-scale demonstration and commercialisation of IGCC will also help in bringing the initial costs down. Based on the results of the economic feasibility assessment, it can be seen that in the foreseeable future economic considerations favour the addition of coal-fired supercritical units to improve the
efficiency of power generation while simultaneously retaining the affordability of supplied electricity and may remain the favoured policy choice for India.

Other studies estimate that at the current level of gasification technology for low-rank coals the cost of electricity (COE) for IGCC with CO₂ capture is close to the COE from PC plants with CO₂ capture for sub-bituminous coals and may be greater for lignite and conclude that because of the economic advantage of their sunken investment most existing PC plants would probably just pay any taxes imposed for emitting CO₂ emissions (Holt, et al., 2003). This raises the broader question about the state of the environment and the viability of clean coal technologies in balancing the objectives of energy sustainability and affordability.

Conclusion and Policy Implications
This chapter explores the techno-economic feasibility of clean coal technologies for India’s coal power systems. The assessment is carried out in the context of the evidence and findings from Chapters 5, 6 and 7, which establish that coal will remain prominent for India’s energy pathways in the future and will play a prominent role in its growth and development. India faces the balancing act between economic growth, alleviating energy poverty and reducing carbon emissions with indigenous resources at the lowest cost. Balancing these objectives with global NetZero objectives proves challenging based on the current policy set-up, regulatory framework and the current set-up of global energy governance arrangements, presenting grave prospects for limit global temperature rises to 1.5 °C.

Integration of suitable clean-coal technologies that can bring about a plateauing, and a gradual decline in India’s emissions will need global efforts and new investments of a staggering proportion ($1.4 trillion additional funding as estimated by IEA, 2021).

India’s current pathways cause the long-term global crisis; a broader framing and a closer appreciation of the scale and nature of this problem is needed as provided by this PhD research. The results from the SD model unravel the nature of this problem: India will fail to reduce its emissions at levels needed for Net Zero in 2050 simply with:

- **efficiency improvements and transition to HELE super-critical coal-fired power plants**: these can reduce the emission intensity of generation, but the carbon-emission will increase;
- **very high integration of renewable-based installed capacity**: while these provide a diversified mix of generation and significantly lower the emissions through net avoided emissions; emissions increase as long as carbon-intensive sources continue to play any significant role in the generation mix;
• the combination of the above two to reduce India’s emissions to achieve NetZero.

Based on the evidence from India-coal research, it can be concluded that the only way India can reduce its emissions while continuing to use coal-fired power is through the adoption of advanced clean coal technologies enabled with CCS. IGCC technologies, while not yet commercially realised, offers significant technological prospects for emission reduction. The study shows that there is very little change in the relative competitiveness between various supercritical or ultra-supercritical PC technologies. Supercritical PC without post-combustion carbon capture equipment offers the cheapest generation source despite its relatively lower efficiency as compared to IGCC technologies.

IGCC technologies underperform in India’s context on economic consideration and significantly increases the cost of electricity. Without international support and cooperation, the environmental advantages associated with IGCC plants in India do not outweigh its higher cost under the current scenario. This observation is supported by an almost total lack of policy direction offered by the Indian government on IGCC or indeed on a roadmap for CCS integration in India’s carbon-intensive generation systems. Several other factors will also play a part, such as greater commercialisation in IGCC technologies internationally and collaboration over R&D. Changes in environmental legislation mandating retrofitting of carbon capture in all coal-based generation improve the competitiveness of IGCC with supercritical technologies and can create favourable signals for faster deployment of IGCC with capture for electricity generation in India. Mandating carbon capture and storage technologies globally and reforms in India’s regulatory setup creating avenues for greater foreign investment in coal power-generation systems will also be needed; however, their wider impact on energy poverty alleviation also needs to be considered.

In summary, while all the relevant clean coal technologies are either under consideration or, under some stage of R&D in the country. Each of these offers a set of benefits for addressing a specific set of challenges. But it is highly unlikely that without significant restructuring and global efforts, India’s generation mix in the future will be dramatically different from the current mix. Having outlined the clear advantages of IGCC with capture in helping reduce carbon emissions, and the risks around its limited commercialisation and high costs, a technology roadmap that identifies the development path goals for meeting the envisioned goals is presented. This technology roadmap is illustrative and based on the reports analysed in the course of this PhD research and findings from the technological and economic assessment. This roadmap is meant to describe one possible set of options that were considered within the scope of this study. Given the limitations of this research, this is not unique or authoritative. The development of a national roadmap, however, may be an important step for engaging various stakeholders, interest groups and institutions to coordinate and participate in the
development of multiple technologies. The technology road map in India’s context may follow along the trajectory listed below:

**Ongoing and near-term (before 2025)**

- Improved coal recovery, coal beneficiation, reduction in cost
- More emphasis on fluidised bed combustion; super-critical (SC) and ultra-supercritical (USC) power plant boilers
- IGCC demonstration at and above 100 MW
- Pilot-scale studies on coal liquefaction
- CCS Pilot Scale

**Medium-term (now-2030)**

- USC Power Plants
- Enhanced energy recovery from coal (Coal Bed Methane, Underground Coal Gasification)
- Demonstration of larger-scale IGCC and coal to hydrogen pilots
- Pilot-scale Pressurised Fluidised Bed Combustion
- Integrated Gasification Fuel Cell Cycle (IGFC)
- Pilot-scale Zero-Emission/ CCS technologies
- Demonstration of IGFC and coal to hydrogen

**Long term (after 2030)**

- The commercialisation of Zero Emission Technologies
Chapter 8. Summary and Conclusions

This concluding chapter will look into some of the implications of the findings of this thesis on how feedbacks between the current policy choices and emerging resource pathways can affect the energy system transition and its wider implication for the existing processes and mechanisms responsible for governing energy systems. It will do so primarily by briefly summarising the answers to the research questions outlined in the introduction to this thesis. These summary answers will be provided only briefly to avoid unnecessary duplication with observations and results already made in each chapter. The conclusion will, however, aim to eke out further implications for the theoretical concepts on the energy governance framework which have framed the qualitative document-based analyses as well as in light of the insights gathered from model-based enquiries into the impact of emerging dynamics of oil and coal on decarbonisation objectives.

The philosophical underpinnings of this research are premised around the role of energy as the lifeblood of our economies and critical infrastructure that affects all our lives and virtually every activity of modern human society. The contemporary energy system, representing the entire energy value chain including the way energy is accessed, transferred, and transformed into various forms for its application in heating, cooling, lighting, and transportation, represent a complex mesh of interrelated and transnational components comprising of elements from physical, technical, social, political and economic systems. The way these variables interact is often also unique depending on the inherent social, economic, and political context, which in turn results in very different trajectories emerging for specific parts of the energy system, often creating gaps between locally pursued energy policy objectives and globally desired outcomes.

Given the capital-intensive nature, longer lead times, and high social costs involved with energy systems, decisions concerning energy resources have historically been subject to state and strategic control, and global systems and institutions entrusted with energy governance have mostly been restricted into playing supporting roles, limited to advising and advocating, based on specific need and situation. However, the growing immediacy of the global climate crisis and the inability of the existing systems to jointly address the challenges promptly stresses the need to examine and assess the efficacy of the current framework responsible for implementing energy policies, and reform them suitably and urgently so that they are capable of effectively addressing the challenges that disrupt the transition of energy systems towards NetZero, secure, affordable and just energy pathways. The self-conflicting nature of some of these objectives indicates that the transition will be complex entailing social and political risks. There, however, is considerable assistance with the
increase of public awareness on the adverse effects of climate change and changing public perception asking for immediate and urgent climate action. And while, the time may be right, for this transformation to be successful, a global, future-looking, and evidence-based approach will be needed involving the right actor-network-institution linkage with greater legitimacy and mandate to effect change across various related components and domains of energy systems.

**Answering Questions and Conceptual Implications**

This thesis has set out to answer some specific questions about the key factors that will play a decisive role in determining the success, or failure, of energy systems transition to decarbonised pathways while balancing domestic and regional priorities with global objectives not just in an attempt to address inconsistent and limited understanding of the impact of emerging dynamics of complex system feedbacks, but also because these have lasting and damaging implications on global climate goals. The emerging dynamics of resources (studied using global oil exchanges emerging from continued volatility in its price levels) and continued resilience of fossil-fuel-based economies (studied using continued coal-fired power in India) pose significant challenges to global NetZero objectives, which cannot be addressed by policy silos or incoherent frameworks. Examining the scenarios that emerge from feedbacks between various parts of energy systems through model-based studies also has broader relevance for assessing the suitability of the current framework of mechanisms and processes responsible for governing energy systems in addressing the contemporary issues exacerbated by uncertainties.

A set of questions that were outlined in the introduction to this thesis were:

- **How will the emerging dynamics of resources impact the future transition of energy systems towards decarbonised pathways, and the global governance of energy?**
- **How will the long-term dynamics of fossil fuel resources, notably oil and coal, impact the future of energy systems transition, considering new policy and market feedbacks?**
  - **Sub-question 1: What will be the future effect of oil price points on the oil demand?**
  - **Sub-question 2: What will be the impact of India’s overlapping energy policy objectives on coal use for power generation and India’s carbon emissions pathways?**

As suggested in the thesis introduction, the conceptual framework of analysis adopted here has followed along a mixed-method approach using both qualitative and quantitative methods, and in Hall’s words, “...borrow[s] from multiple schools of thought...” (Hall, 2010:220). The conceptual framework has been utilised to structure this thesis as well as to establish a closer appreciation of the existing processes and frameworks related to global governance and energy systems and the
trajectories likely to emerge from interactions between various interacting parts. As mentioned in
the introduction of this thesis, this PhD research lies at the intersection of four fields, including
systems theory, governance, energy studies, and transitional governance. This is very much in line
with the general conceptual foundations laid out for complex systems governance by previous
studies, notably by Keating and Katina (2019), stating that complex systems governance lies at the
intersection of fields such as governance, systems theory, and management cybernetics
(represented through transition governance studies) (Katina, 2015; Keating & Katina, 2019; Katina et
al., 2020).

The introduction also brings to view the context and motivation guiding this thesis development,
highlighting the huge gap that currently exists in the energy governance capacity to support the shift
to a Net Zero economy. Energy systems globally are undergoing significant changes due to the
emergence of new technologies, new priorities such as NetZero transition, and externalities created
by global concerns, not just, but notably, climate change. Of these, a shift to the NetZero economy
creates the most noticeable contradictions, given the continued prominence of oil and coal in global
energy systems, poised to dominate the energy governance reform agenda in the near future. A
UNEP (2019) study shows governments around the world plan to produce 120% more fossil fuels by
2030 than what would be consistent with limiting warming to 1.5°C or 2°C (UNEP, 2019). IEA’s “Net-
Zero by 2050” report reveals that even if all the countries that are committed to NetZero pathways
succeed to fully meet their targets, there will still be 22 billion tonnes of carbon dioxide worldwide in
2050 which would lead to a temperature rise of around 2.1°C by 2100 (IEA, 2021). The realities pose
challenges of an epic proportion for the governance of energy systems globally.

But transforming energy systems, as often recognised as a societal response catalysing paradigmatic
shift towards decarbonisation, may not be practical, or even, feasible given the shared attributes
between energy systems and the core characteristics for complex systems (Cherp, Jewell, &
Goldthau, 2011). The paradigm shift theory as proposed by Peter Hall (1998) and developed over the
years by other scholars, notably Oliver and Pemberton (2004) and Kern, Kuzemko, Mitchell (2010;
2014), suggest a third-order change, which traditionally is marked by radical changes in all parts of
policy machinery and discourse, as a requisite option for facilitating the kind of transition needed by
energy system to reach NetZero pathways. And while climate change, and the urgent need to transit
to NetZero, provides a strong narrative of crisis creating the window of opportunity that present the
potential to and opportunity for reforming the existing institutional structures to implement change,
as suggested by Kingdon (1984), an incremental, or third-order, change in governance has not yet
occurred, as is typically expected to take place after periods of crisis, uncertainty or shocks. What
emerges through the analysis of the global energy governance framework is the prevalence of actor-network regimes, competing for greater legitimacy and control, self-organising into acceptable ways into areas of mutual interest.

There is hope among energy governance scholars that the New Energy Governance framework, with its revised scope and objective and the very wide set of actors will be effectively in heralding the energy systems transition towards secure, sustainable and equitable pathways. But the inability of the existing governance frameworks only becomes evident and apparent when analysed against the set of results generated by model-based studies and modelled scenarios. The thesis establishes the relevance of complex systems tools for carrying a closer review and assessment of the global governance framework. Traditionally, governance studies use doctrines, theories, and methods from Public Policy, Public Management, and New Public Governance; occasionally concepts from international relations and economic theories are also used, either on their own or in combination with the former. Each of these approaches has proven benefits as established by a huge body of research work undertaken over several decades. However, with the emergence of transnational issues such as climate change, the need to maintain energy and international security, alleviate energy poverty, challenges related to energy systems transition have acquired the characteristics of wicked problems (Churchman, 1967), often creating policy inertia or unintended consequences (Sterman, 2000). These problems typically emerge in socio-technical settings involving several components such as technology, systems, institutions, and people, traits exhibited by contemporary energy systems, making complex systems theory and post-normal scientific approaches, which use uncertainty, a multiplicity of perspectives, and a wider problem-solving framework, more suitable than linear-reductionist thinking (Funtowicz & Ravetz, 1993). The inevitable tension between qualitative and quantitative approaches as a better approach is best avoided in favour of appropriateness of method to the specific context of the research, and in doing so this thesis joins others such as Patton (1990) in ‘paradigm of choices’, rejecting the orthodoxy of methodology. By erring more on the side of being overt about the complexities of change as dictated by the social, economic, and political realities and context, this thesis is more about portraying the real-world scenarios that can emerge under a set of conditions. By borrowing from a range of different fields, a set of unique inter-relationships and insights emerge that add unique value to the literature.

System Dynamics and Global Energy Governance

The relevance of this purposeful mixing of methods used in this research become apparent given the confluence of various factors: inherent structural attributes and complexities of energy systems; the challenges it must address; and its transnational characteristics. Chapter 2 establishes that with the
indomitable shift of energy systems towards extremely complex systems, more strategic thinking tools will be needed to enable a successful transition of twenty-first-century energy systems towards the myriad sought objectives (Cherp, Jewell, & Goldthau, 2011).

The problems stemming from dynamic complexity, interdependencies, and exchanges within energy systems pose a serious dilemma for traditional forms and modes of governance, while the traditional static arrangements not just prove incapable of dealing with uncertainty and nonlinearity (Cherp, Jewell, & Goldthau., 2011). The systems thinking paradigm helps to understand how various parts of the system are connected and identify sensitive parameters and leverage points. As described by Senge in his seminal work, The Fifth Discipline, the structure of a system influences its behaviour, and ‘more often than we realise’ the systemic behaviours are influenced by the basic interrelationships *within a system* (2004). The systems thinking and complexity perspective as applied to societal and governance changes suggests that uncertainties and non-linearities are important features that determine societal change, and these are often seen to follow specific patterns, dynamics, and mechanisms. A closer appreciation of the dynamics of changes can be gained by understanding the emerging patterns and mechanisms. This can offer a basis for influencing and affecting it.

System dynamics, a complex systems method, is particularly well suited for this PhD research as it explains the nonlinear behaviour of complex systems over time using stocks, flows, time-delays, table functions, and feedback loops. Developed originally to help managers improve their understanding of management and industrial processes, SD has been in use for policy analysis and design for many decades.

While the systems thinking paradigm has been applied as an analytical approach to address complex patterns of interactions in sociology, economics, ecology, policy, and organisational sciences since the 1960s; but their ‘explicit introduction into governance studies’, through the concepts of governance and governance reform has not been adopted. This is even though the SD philosophy that has proven successful in helping improve business and management processes can also provide deeper insights into the governance reform process. While more research is needed to fully integrate the use of modelling and simulation to improve system performance by purposeful ‘design, execution, and evolution of the metasystem function necessary to provide control, communication, coordination, and integration of a complex system’, other studies have established the use of modelling and simulation for enhancing the development of complex systems governance (Katina, Tolk, Keating, & Joiner, 2020). The lack of a hybrid complex systems method for energy governance poses challenges, addressed in this thesis by following a mixed-methods approach and by
triangulating the results from SD models with the concepts and theory from governance and energy governance literature. In doing so, this PhD research demonstrates the suitability of a mixed-methods approach using qualitative governance with complex systems thinking. The holistic combination of both qualitative governance with quantitative systems represents a methodological innovation in energy studies.

### SD Models of Emerging Dynamics of oil and coal

Complexity science and its associated model-based studies are indeed an invaluable tool for capturing the complexity emerging through interaction between various layers of energy decision-making process across time and space. Chapters 1 and 2 explore and establish the suitability and relevance of employing a systems-based approach to this thesis. Given the high degree of non-linearity in energy systems, it is difficult to otherwise conceptualise and solve a model analytically, or to assess the long-term impact of policy decisions. SD, on the other hand, provides a powerful tool for policy analysis using inbuilt tools such as sliders and switches, which help to visually determine how and which parameters in the system can considerably affect the behaviour of whole systems.

Given the crucial relevance of oil and coal in the context of decarbonisation and NetZero objectives and the emerging geopolitical landscape, their emerging dynamics are hugely significant for future energy systems. Oil and coal together pose the widest set of challenges to decarbonisation objectives given their role as the biggest sources of primary energy and as the largest emitters of greenhouse gases, but also in ensuring access to energy for quality of life and economic development. To delve deeper into the evolving dynamics of oil and coal a range of scenarios associated with their continued consumption, separate SD-models of global oil and coal-dominated power generation in India is developed. The insights from these models together provide an insight into the impact of long-term dynamics of these resources on the desired energy systems transition. This analysis is aided by examining and answering two sub-questions that respectively assess the impact of oil price points on determining its future dynamics, and the long-term impact of India’s energy policies on the counties emissions trajectories. These, in turn, provide the answer to How will the long-term dynamics of fossil fuel resources, notably oil and coal, impact the future of energy systems transition, considering new policy and market feedbacks?

**Oil price and demand dynamics:** The SD model of oil analyses the impact of future changes through a set of modelled shocks on macro-level dynamics of global oil exchanges and answers the question: What will the future effect of oil price points on the demand of oil? The SD-based analysis facilitates a rational representation of physical stocks and flows as well as nonlinear causal linkages that drive
decision-making in the global oil system, providing insights (intuitive and counter-intuitive) into the macro-level dynamics of global oil exchanges and allowing assessment of the potential impact of future changes in system behaviour. Shocks, or sudden changes in the system, across all the test simulations result in damped oscillations in oil prices, broadly consistent with real market behaviours. These oscillations represent a period of ongoing readjustments between supply and demand levels of oil mediated through price points and brought about by policy directions and signals. Disruption or shocks causing a shortage of oil results in an inflationary effect on prices; while oversupply causes the prices to crash. With the notable caveat that the model is initiated in equilibrium, these oscillations remain in the system for some time, before returning to the original equilibrium price or retaining a new oscillation level. Supply shocks result in a long-term reduction of demands with end-users switching away from expensive and insecure oil.

The model presents valuable insights into a set of scenarios from enduring transition away from oil in an anticipated response to climate change. Countries are likely to respond differently to climate-induced consumption cuts depending on their local socio-economic and political context. Three representative blocks were constructed as relatable cases to represent key global consumers: China; India; and the Rest of the World-dominated by OECD demand centres. Demand reduction induces price response, which in turn determines consumption levels. A strong decrease in oil consumption in China alone reduces global oil consumption to levels equivalent to demand reduction by the ROW-OECD block. Other countries, like India, adjust their consumption levels depending on prices. A common feature of global oil is continued price volatility over the entire duration of the model.

Oil price volatility has had a significant impact on the global economy in the past, triggering many changes in the world order, such as economic depression, inflation, the concentration of wealth in OPEC nations, and booms and busts in the oil industry (Morecroft & van der Heijden, 1992). Volatile oil prices, particularly low oil prices, has the potential to ‘reduce the competitiveness of renewable energy in the long-run’ and provide short-term stimulus to the economy, thus increasing consumption levels, a challenging prospect for net zero transition (Klevnas, Stern, & Frejova, 2015, p. 3). The dynamics of oil exchanges exacerbate future uncertainties and pose significant risks to climate action.

Model results highlight key windows of opportunities for reform which can ensure that the short-term gains from low oil prices do not outweigh long-term energy objectives. Low oil prices, for example, offer countries a window of opportunity whereby countries can ‘revise their energy pricing by removing subsidies or by adding a carbon price component to it’ (Klevnas, Stern, & Frejova,
Low oil prices may be irreparably damaging to a vast majority of the world’s oil producers, who are dependent on oil revenues to fund their social growth and development (Dale & Fattouh, 2018). With the estimated fiscal break-even price to be around $60 per barrel for the five Middle-Eastern oil producers (Saudi Arabia, UAE, Iran, Iraq, and Kuwait), these OPEC producers would find it difficult to sell higher volumes of oil lower than their fiscal break-even prices against non-OPEC oil producers. Low oil prices may, therefore, incentivise oil producers to diversify their economies. Saudi Arabia can already be seen preparing for a likely low-price regime by launching measures such as its Vision 2030 plan, that, among other things, seeks to grow and diversify its economy (KSA Vision 2030, 2019).

Relevant processes and bodies responsible for global oil governance have a crucial role to play in providing the necessary support and bridging any gaps that force countries to remain locked into using oil. Some of the key bodies and processes that govern oil include IEA, OPEC, Energy Charter Treaty, the International Energy Forum, various development banks, mainly World Bank, G7 (particularly interested in tracking oil prices), World Trade Organisation (WTO), and various International Oil Companies and National Oil Companies, however, these are restricted mandate and capability for address the long-term decarbonisation challenges at a global scale. Effective coordination between oil suppliers and producers and maintaining transparency can be important for hedging the physical markets against price volatility. Effective management of National Oil Companies (NOCs) and International Oil Companies and aligning them to work beyond strategic short-term interest towards global goals will be of key relevance (Boscheck, 2007). Effective governance of NOCs is crucial to address concerns over further disruptions in global oil exchanges emerging from their poor management and performance in various parts of the world (Heller & Kaufmann, 2019). An example of the role that effective governance can play can already be seen through the recent changes that have been initiated as a result of the consolidation of reporting rules by the Extractive Industries and Transparency Initiative (EITI), which is addressing the problems created by the lack of transparency, oversight, and accountability between various governors of oil globally.

Model of Emerging dynamics of coal in India and CO$_2$ emissions: The SD model of coal-based power generation systems in India focuses on the problems of rapidly increasing CO$_2$ emissions from India’s coal-fired power generation systems. Results from the model help to understand the impact of India’s coal future on global Net Zero objectives and address the question: What will be the impact
of India’s overlapping energy policy objectives on coal use for power generation and India’s carbon emissions pathways?

Modelled simulations of electricity system including renewable energy and coal-based capacities, which currently constitutes the bulk of the generation mix show that CO₂ emissions from power generation systems continue to grow consistently into 2050, reaching 4 Gt of CO₂ in the current policy scenario. Efficiency improvements in coal-fired plants result in significant improvements in India’s emission intensity indicating the possibility of India meeting its Paris commitments. Despite an impressive increase in renewable generation capacity over the entire duration of the modelled timeframe, the target of 450 GW by 2030 as set by the Indian Government is not reached. But the overall prospects improve significantly for global decarbonisation and plateauing of India’s carbon emissions with the phasing-off of the sub-critical fleet of coal power plants with coal plants enabled with carbon capture. The study also explores a scenario in which advanced coal technologies with carbon capture and storage are integrated into India’s power generation systems, which results in meeting CO₂ emission reduction targets with coal remaining a part of the energy system. This is a scenario that is often sighted as a scenario where coal is no longer a part of the problem but rather a part of the solution. But this will not be an easy transformation to achieve.

India’s policy choices will reflect its socio-economic and political realities in the foreseeable future. While climate change is a pressing global concern, India’s priorities may remain divided between achieving environmental sustainability and ensuring access to energy at affordable prices for improving quality of life for its people and economic development, not essentially in this order. Model results and the technological feasibility assessment establish the suitability of advanced zero-emission coal technologies, particularly IGCC-with capture, for use with Indian coal and for achieving global decarbonisation and NetZero objectives. The technological feasibility assessment presented in this thesis also establishes the suitability of many gasifier technologies, notably fluidised-bed and moving-bed gasifiers for use with high-ash Indian coal, but only to a limited extend. And while the environmental benefits of IGCC technology exceed all other coal-based technologies in India, the cost of electricity produced using IGCC units was found to be significantly higher than the cost of electricity produced using supercritical units. Based solely on economic performance, single-point calculations favour post-combustion capture technologies over IGCC. The Risk-Reward analysis using Monte Carlo simulations based simply on narrow economic considerations also shows that investment in IGCC does not appear economically viable until the time that annual fixed costs associated with these are significantly lowered. A radical change in direction in policies and a massive demand-pull strategically engineered through policy instruments will be needed for IGCC to
systematically replace the existing coal-power fleet in India. All the relevant stakeholders will be required to redirect their efforts and pool in available resources for this transition.

Recent studies elsewhere suggest that India’s energy choices are likely to be subject to stricter scrutiny in the years to come. A Brookings study (2021) indicates that the US may offer its support to help India transition away from coal by mobilising funding from apparatuses such as United States Agency for International Development (USAID), Development Finance Cooperation (DFC), and other relevant international banks and agencies (Busby, et al., 2021). While a range of other measures may become available, funding advance-coal technologies can be an expensive but quick fix to India’s coal conundrum, one that the Government may be willing to accept, with outside support, as it addresses concerns related to secure supply of imported fuels and intermittency of renewable power.

The thesis highlights a huge gap in the global governance framework in addressing the challenges facing the decarbonisation of coal-fired power generation in developing countries, with the use of India as a reference case. Analysing the efficacy of the current governance framework has been an important aspect of this thesis. Global governance arrangements and processes analysed in chapter 3 have a crucial role in addressing the existing barriers and challenges. Analysed against the results from the SD model on coal, it can be seen that currently, an adequate institutional response from global governors of energy with a mandate on coal has not been forthcoming.

The contemporary global energy governance arrangements fall short of meeting pressing needs to stimulate markets, tackle externalities, alleviate energy poverty and address the various trade-offs between maintaining security, sustainability and affordability of energy supplies (Florini & Sovacool, 2011). Despite the signalled desire to clean India’s power-generation systems, the business-as-usual prevails. Various studies reviewed in relevant chapters highlights that currently the governance landscape is dominated by intergovernmental institutions or UN bodies, more notably, the UN Framework Convention on Climate Change and its Paris Agreement (UNFCCC/PA), the International Energy Agency (IEA), the World Trade Organization (WTO), the Group of 20 (G20) and the World Bank, who can set rules, provide financing and investment, share knowledge and learning. A number of issues prevail, including the following as identified by Florin & Sovacool (2009:5246):

- Limited capacity to develop necessary rules and channel the necessary resources to meet the energy systems transition challenges, due to limited remit, membership, mandate, etc.
• Fragmentation of cross-border energy governance, to the degree it occurs, by energy source or sector.
• The near impossibility for any inter-governmental or central organization or regime to collectively negotiate with all the major players to harmonize all their resources and energy policies
• And, significantly for this study, that energy agenda globally will be governed by an array of different types of actors, with widely ranging claims to legitimate authority, attempting to set rules on different parts of energy montage

By modifying the criteria of search, however, and looking beyond a central capacity significantly improved potential emerge for the GEG capacity for addressing the challenges facing energy systems transition. Regime complex frameworks and polycentric arrangements offer significant potential in their capacity to address transnational challenges by facilitating ‘reflexive governance’ (Voss & Kemp, 2005) for energy systems (or, other large technical systems) which are intertwined with multi-actor, multi-network “regime-complexes” (Raustiala & Victor, 2004) and where transformation can be seen to be limited by the ‘limits of conventional steering approaches’ to achieve the desired policy objectives (Voss & Kemp, 2005, p. 18).

As Colgan et al. (2012) rightly argue, ‘no single account can perhaps match-up and cover the range covered by the full energy regime complex’, but collaborative arrangements or complexes could have significant potential given the nature and scale of change needed. A loose mesh of mutually reinforcing, ‘narrowly-focused regulatory’ nested regimes, as suggested by Keohane and Victor (2011), created by the diversity of structures and interests that are inherent in the political, social and geopolitical landscape of energy, can be effective in negotiating necessary arrangements useful for addressing specific elements of the transition. By ‘simultaneously encouraging participation, providing coordination, drawing on or delivering reliable information, promoting thoughtful deliberation and decisions, and instating equitable and legitimate incentives for compliance’ (Andrews-Speed & Shi, 2016: 200), there can be a range of benefits in including either or both of these approaches for promoting renewable energy, improving energy efficiency and reducing CO₂ emissions. Further research is needed to examine their suitability in India’s context. Integration of suitable clean-coal technologies that can bring about a plateauing, and a gradual decline in India’s emissions will need global efforts and new investments of a staggering proportion ($1.4 trillion additional funding as estimated by IEA,2021).

And, significantly for the global governance for energy, given the current landscape of governance arrangements, there needs to be a wider agreement that the energy agenda globally will be
governed by an array of different types of actors. These reflexive polycentric regime complexes need to be apportioned greater validity, mandate, legitimacy and resources to set rules on different parts of energy montage and facilitate change in areas that need intervention. Intergovernmental bodies such as the IPCC, trans-national organisations-run by non-state actors, international organisations, partnerships (such as Powering Past Coal alliance), organisations such as the World Health Organisation that consider welfare aspects, United Nations Human Rights Council, United Nations Development Programme, welfare development banks (such as the World Bank) and many other state-non state hybrids and NGOs all have a key role to play and should be brought on board. With effective cooperation and restructuring through this complex, Global Energy Governance can carry out the following key functions:

- Align actors across countries based on their interests and concerns to work together on shared goals.
- Facilitate cooperation and enable action by addressing interdependencies and competitiveness concerns.
- Promote transparency and accountability.
- Provide a shared pool of resources and means of implementation.
- Promote RD&D, knowledge and information transfer, and learning by sharing.

The modelled results and scenarios provide extremely relevant and forward-looking insight into factors that need urgent consideration and will determine the success of global climate ambitions. While a more in-depth review and more focussed examination into the energy system governance reform is needed, the review of governance framework assessed against the scenarios from model-based studies presented in this thesis suggests that the governance processes must adapt flexibly with the evolving dynamics of system behaviour, and so must its actors, networks and processes. These networks and linkages, suitably equipped and structured, can in time modify the structure of the system through policies and practices negotiated between various parts of the system.

Much of the theory of change in governance literature is focused on assessing how change occurs and explore the question of the depth of change. Theories of paradigm shift and narratives of change associated with traditional changes in the paradigm change help to explore a key element related to the extent to which the Global Energy Governance paradigm has undergone a paradigm shift. Based on the paradigm shift literature and the review of the current global energy framework, changes across all the five proposed levels of the paradigm-shift framework as outlined in the studies by Thomas Kuhn (1962), Hall (1993); Shackley & Green (2005) and Kern & Mitchell (2010) are 215
assessed. Scholars of paradigm change theory (Wheatley, 2006) maintain that only with total shift across all levels of a given system, do systems respond to change. Findings from a high-level assessment across the 5-levels of paradigm change framework as applied to Global Energy Governance show that significant changes have taken place over the last two decades in the Global Energy Governance Paradigm, predominantly with an increased global awareness of global climate crisis and its impact on many other policy areas. The paradigm shift framework as explained by scholars such as Hall (1993) implying whether a clear break or departure from past policies is important in retrospectively analysing change, however, this thesis establishes that there is merit in avoiding the temptation of forming a conclusion on the efficacy of energy governance frameworks or drawing a conclusion on the degree of paradigm shift without assessing the ability of governance framework in affecting change and its suitability to emerging challenges. As such, this thesis has set itself apart in that it has considered change in light of the efficacy of the framework towards implementing goals and objectives. The evidence-bases and insights from scenarios considered together with theories of governance and governance reform are therefore a forward-looking and rational approach to amend the global energy governance framework in a way that makes it effective and capable of addressing the energy system challenges. Based on various assessments carried out in this research, it can be established that major reform across the policy/governance institution level will be needed for the Global Energy Governance arrangements and processes to successfully deliver on various outlined objectives and to help energy systems transition to NetZero and equitable pathways. While a logical and straightforward approach would be to call for the creation of a new Global Organisation one that had a mandate on all energy issues globally, but such a body would be extremely bureaucratic and a difficult one to create. Recognising this problem of incoherence, former Prime Minister Cameron, at the 2011 G20 summit said:

“There are a large number of established institutions and processes ......in ......areas such as energy. The solution in many cases is not formally changing mandates or creating new bodies. Such changes can consume huge amounts of political energy. ........Rather, existing institutions should be given clearer and stronger political direction to work together”.

Somewhat crucially, the assessment of the paradigm change framework of governance shows that the framework of actors and institutions remains broadly unchanged, or has only partially changed, across the assessment period. It is against this level that radical changes or systemic restructuring may have the widest impact in affecting Global Energy Governance reform. This thesis suggests that there may be merit in a polycentric arrangement of regime complexes that:
• Sets the vision; structures the problems and establishes the common principles,
• Sets the working agenda; establishes coalitions; gets agreement on issues,
• Mobilises resources and actors, and
• Evaluates results and adapts flexibly and non-intuitive to emerging dynamics of systems.

SD models provide not just the rationale that frames the need and process for systems thinking but also helps to identify the inherent conditions or policy levels with which such systems can (or cannot) be steered in a way that can lead to successful energy systems transition in the long run. Effective governance reform will only be successful if it is undertaken at the back of insights into the dynamics of the system: insight into how the system works is an important prerequisite for effective governance (Loobarch, 2010).

The theory of structuration and transition governance helps to ideationally answer the question of how will changing dynamics of resources impact the future transition of energy systems, and the global governance of energy. The changing dynamics of resources are in part a result of both external and internal non-linear changes brought about by steered policy direction over a period of time, these changing dynamics in turn will result in the restructuring of energy systems towards various objectives. As Loobarch (2007) suggests concerning the transition of complex systems, these adapt to both external and internal changes that are ushered through steered changes in policy direction which are brought about, among other things, by the governance processes-through the long and tedious process of agenda-setting and implementation of policies. System structure, according to Anthony Giddens’ theory of structuration, is an outcome of previous practices, and these structures dictate the feasibility of processes that make practices possible. Therefore, long-term thinking is required for effectively steering the system, which over time will shape and determine its emerging dynamics. Adapted from Loobarch’s (2010:167-168) transition governance principle for complex dynamic systems, the following principles of governance for a complex system can prove effective:

- Governance of a complex system depends on the dynamics of the system: efficient energy governance, therefore, will be determined by how energy systems work, and insight into system’s behaviour are an essential precondition for effective governance;
- For managing complex energy systems disequilibria as well as equilibria must be used: stocks, or the state of a system, create delays, capture memory, and are responsible for disequilibrium dynamics of the system, and the dynamics of stocks and flows yields useful insights into problems, as shown by SD models of oil and coal developed in this study;
• Shocks or short periods of disequilibrium provide opportunities to direct a system towards its desired trajectory

• Timely intervention through policies and processes is crucial for avoiding policy failure and undesirable outcomes, this is particularly relevant for the reform of the energy governance framework for achieving NetZero objectives.

• *Wicked* problems such as climate change and decarbonisation of energy systems require long-term thinking using a complex system approach, given the long lead time for planning and securing investments required in new, emerging technologies and systems solutions that cannot be quickly implemented.

• Actors and institutions play a key role in the iterative reframing of policy agenda and mobilising support for policies.

**Future work and final reflections**
The research work undertaken in this thesis is aimed at assessing the efficacy of frameworks and processes of global governance of energy systems through a closer inquiry on the future oil exchanges and India’s policy on coal-based power generation. Because of its applied contribution to Global Energy Governance scholarship, simpler aggregated models have been chosen over more disaggregated and detailed models. Improvements in the current work can be brought about by modifying the selected boundaries. Two broad areas of work can be undertaken in the future to extend the scope of this research and improve its findings.

The first broad area includes refinement in model parameters and boundaries. In Chapter 4, nonlinear relationships are used in the model using table functions to formulate and capture their effect on demand and supply paradigms, these could be replaced with explicitly calculated endogenous variables. The model results will offer further clarity if the Effect of Oil Price parameters, GDP Growth Rate-Oil Demand Multipliers, and Price Multiplier on Shale Production are all endogenously determined. Incorporating financial instruments in the model will also add value, however, it will make the model clunkier and difficult to manage. Model results in chapter 6 can offer further insight by including investment mechanisms and elements related to investment decisions. These parameters could be driven by global carbon price signals and India’s response to them. This could present significant insights into the implications of carbon prices on India’s energy pathways.
There is a lack of literature exploring the visualisation model of energy systems governance, with a need to broaden the application of the SD modelling paradigm, given its proven capability of explaining emergent system behaviour over time and integrate it with other suitable paradigms to fully address relevant aspects of complex systems governance. Such a hybrid model could be used to develop insights into the structural relationships, context, and systemic deficiencies existing in governance of a given complex system. This will, however, need to be appropriately resourced, and evidence-based, incorporating proper risk-reward assessment against all the relevant aspects. More collaborative work with Global Energy Governance actors would be needed to further refine the scope of this work. Data will help to provide a pool of enabling factors that can strengthen Global Energy Governance.

Final Reflections

As a final comment, it might be worth reflecting that the qualitative aspects of the research focusing on governance framework assessment could have been broadened to include wider perspectives from relevant actors and inclusion of concepts and theories of energy justice. This is despite attempts made in the first three chapters to undertake a suitably comprehensive analysis of the literature. Arguably—this has much to do with the timeframe within which the analysis was conducted and the emerging landscape of energy systems governance, where changes are underway, and a drastic reform is expected after COP-26 in Glasgow. What is less discernible, is the precise direction in which this change will manifest, but there is evidence that regime-complexes are likely to evolve as a major process where policies will be negotiated and a key instrument with responsibility and oversight for implementation.

These regime-complexes will gain mandate and legitimacy with a wider representation of diverse actors and regional realities emerging from the social, economic, and political landscape and the context in various countries. Oil and coal may continue to occupy a prominent share in the global energy mix, aided by a set of very different factors that favour their continued use in the future, with extremely worrying prospects for the global environments, unless wider systemic reforms are instituted. More international support and collaboration will be needed to aid and abet the transition away from these polluting fossil fuels, but such collaboration will only materialise or succeed with a deeper understanding of the long-term dynamics of interaction between policies and energy sub-systems.

Climate change and energy poverty are two of the biggest challenges of the 21st century, and solutions to one cannot take place at the expense of the other. Ways to concurrently deal with both
these transnational, cross-border, trans-market issues, pose an existential threat to our lives and ideals will need to be all-inclusive, long-term, and timely. Technology innovation may perhaps be at the heart of the solution, but R&D and collaboration will be key to addressing challenges associated with adoption and large-scale deployment.
Appendix A Model Documentation

This appendix gives the documentation of all variables, data inputs and other assumptions for the system dynamics models produced for this thesis. The Emerging Oil Dynamics and Global Exchanges Model begins simulation in 2015 and runs for 50 years. The time step for this model is 0.125 year. The main sources of data are BP Statistical Review (2017), IMF and WorldBank (2019(a)). The model is initialised at a price of 100.31 $/Barrel. The non-linear table functions have been estimated based on observed trends. The formulations from Sterman (2000) are used for the hill-climbing structure and other formulations are based on common relationships found in various systems dynamics tutorials and helps available online.

The India Coal Generation Capacity and CO₂ emission model is initialised in 2000 and runs for 50 years. Time step for this model is 1 year. The main data sources for this model are BP Statistical Review and Central Electricity Authority. The value of switches used in the model ranges between 0 and 1. The non-linear relationships are based on information gathered online and during interaction with Indian officials from The Ministry of Coal and Railways and Central Electricity Authority in 2017-2018. These models will be made available on a publicly available website.
A1. Documentation for Emerging Oil Dynamics and Global Exchanges model

1. Average GDP Growth Rate = 2.5
   Units: Dmnl
   Average GDP Growth Rate of the world (IMF Data).

2. Breakeven Price = 50
   Units: $/Barrel

3. Change in Oil Price = (Indicated Oil Price - Oil Price) / Oil Price Adjustment Time
   Units: ($/Barrel)/Years

4. China Demand = China Demand Factor * China GDP Growth Rate - Oil Demand Multiplier * China Reference Demand * Effect of Oil Price on China Demand
   Units: Barrels/Year

5. China Demand Factor = 1
   Units: Dmnl

6. "China GDP Growth Rate - Oil Demand Multiplier" = Sensitivity of China's Oil Demand to GDP Growth Rate (China's GDP Growth Rate)
   Units: Dmnl

7. China Reference Demand = 3,917,910 * 1000
   Units: Barrel/Year

8. China's GDP Growth Rate = 6.9
   Units: Dmnl

9. Consumption Rate = (Total Oil Stock / Oil Demand Adjustment Time) + Total Oil Demand
   Units: Barrel/Year

10. Demand Adjustment Time = 1
    Units: Year

11. Effect of GDP Growth Rate on Demand = Sensitivity of Growth Rate on Demand (Average GDP Growth Rate)
    Units: Dmnl

12. "Effect of Oil Demand/Supply Coverage on Price" = "Sensitivity of Price to Oil Demand/Supply Coverage" * ("Oil Demand/Supply Coverage") + ("Relative Oil Demand/Supply Coverage" * 0)
    "Sensitivity of Price to Demand/Supply Balance" ("Demand/Supply Balance")
    Units: Dmnl

13. Effect of Oil Price on China Demand = Sensitivity of China Demand to Oil Price (Oil Price)
    Units: Dmnl

14. Effect of Oil Price on India Demand = Sensitivity of India Demand to Oil Price (Oil Price)
    Units: Dmnl

15. "Effect of Oil Price on Non-OPEC Production Rate" = "Sensitivity of Non-OPEC Production Rate to Oil Price" (Oil Price)
    Units: Dmnl

16. Effect of Oil Price on OPEC Production Rate = Sensitivity of OPEC Production Rate to Oil Price (Oil Price)
    Units: Dmnl

17. Effect of Oil Price on RC's Demand = Sensitivity of RC's Demand to Oil Price (Oil Price)
    Units: Dmnl
18. Effect of Oil Price on Shale Oil Profitability=Sensitivity of Shale Oil Production to Oil Price
Units: Dmnl

19. Effect of Oil Price on US Conventional Oil Production=IF THEN ELSE(Oil Price/Breakeven Price<1, 0, Sensitivity of Conventional Oil Production on Oil Price(Oil Price/Breakeven Price))
Units: Dmnl

20. India Demand= Effect of Oil Price on India Demand*India Demand Factor*"India GDP Growth Rate-Oil Demand Multiplier"*India Reference Demand
Units: Barrels/Years

21. India Demand Factor=1
Units: Dmnl

22. "India GDP Growth Rate-Oil Demand Multiplier"=Sensitivity of India's Oil Demand to GDP Growth Rate(India's GDP Growth Rate)
Units: Dmnl

23. India Reference Demand=1404885*1000
Units: Barrels/Year

24. India's GDP Growth Rate=7.99
Units: Dmnl

25. Indicated Oil Price=Oil Price**"Effect of Oil Demand/Supply Coverage on Price"
Units: $/Barrel

26. Initial Oil Stock=91704*0.05
Units: Barrel
(BP Statistical Review estimates Total Oil Production in 2015 at 91,704 Barrels)

27. Initial Price=100.31
Units: $/Barrel
(BP Statistical Review)

28. "Non-OPEC Production Factor"=1
Units: Dmnl

29. "Non-OPEC Production Rate"=MAX("Non-OPEC Production Factor","Normal Non-OPEC Production Rate")
Units: Barrels/Year

30. "Normal Non-OPEC Production Rate"=14,773,375*1000
Units: Barrels/Year

31. Normal OPEC Production Rate= 13,349,145*1000
Units: Barrels/Year

32. Oil Balance Perception Time=1
Units: Years

33. Oil Demand Adjustment Time=1
Units: Years

34. "Oil Demand/Supply Coverage"=Total Oil Stock/Total Oil Demand
Units: Years

35. Oil Discovery Rate = MIN(0,US Shale Oil Production Rate)
Units: Barrels/Year

36. Oil Price= INTEG (Change in Oil Price, Initial Price)
Units: $/Barrel
37. Oil Price Adjustment Time=0.5  
   Units: Years
38. OPEC Production Factor=1  
   Denotes the level of efficiency of utilisation of factors of production such as land, labour,  
   capital and resources.  
   Units: Dmnl
39. OPEC Production Rate= OPEC Production Factor*Normal OPEC Production Rate*Effect of Oil  
   Price on OPEC Production Rate  
   Units: Barrels/Year
40. Other Factors Affecting Demand=Input  
   Demand is affected by this exogenous input, which can be set by the user to a step, pulse,  
   ramp, sine wave, or noise.  
   Units: Dmnl
41. "Perceived Oil Demand/Supply Coverage"=SMOOTH("Oil Demand/Supply Coverage", Oil  
   Balance Perception Time)  
   Units: Years
42. Price Multiplier on Shale Production=Shale Oil Breakeven Price*Effect of Oil Price on Shale  
   Oil Profitability  
   Units: Dmnl
43. RC Demand Factor=1  
   Units: Dmnl
44. Reference Demand for RC=21,484,265*1000  
   Units: Barrels/Year
45. "Reference Oil Demand/Supply Coverage"=1.5  
   Units: Years
46. Reference Production Rate for US Conventional Oil=1,838,140*1000  
   Units: Barrels/Year  
   The U.S. Energy Information Administration (EIA) estimates that in 2018, about 6.5 million  
   barrels per day of crude oil were produced directly from tight oil resources in the United  
   States. This was equal to about 59% of total U.S. crude oil production in 2018.1 Tight oil is oil  
   embedded in low-permeable shale, sandstone, and carbonate rock formations. For 2014, the  
   percentage is scaled down to 50% based on various studies and estimates.
47. Reference Shale Oil Production Rate=1,838,140*1000  
   Units: Barrels/Year
48. Reference US Oil Consumption Rate=6,973,690*1000  
   Units: Barrels/Year
49. "Relative Oil Demand/Supply Coverage"="Perceived Oil Demand/Supply  
   Coverage"/"Reference Oil Demand/Supply Coverage"  
   Units: Dmnl  
   Price rises when Oil Demand/Supply Balance is less than normal, and falls when it is greater.  
   The Sensitivity of Price to Oil Demand/Supply Balance controls the magnitude of the  
   response.
50. "Remaining Countries'(RC) Demand"=Effect of GDP Growth Rate on Demand*Effect of Oil  
   Price on RC's Demand*RC Demand Factor*Reference Demand for RC  
   Units: Barrels/Year
51. Sensitivity of China Demand to Oil Price

\[
\begin{align*}
(18,0) & - (180,3.64), (20,3.64), (40,2.02), (60,1.48), (80,1.21), (100,1.12), (120,0.94), (140,0.82), (160,0.71), (180,0.6), (185,0.49)
\end{align*}
\]

Units: Dmnl

52. Sensitivity of China’s Oil Demand to GDP Growth Rate

\[
\begin{align*}
(0,0) & - (30,5), (0,0), (1,0.13), (2,0.26), (3,0.39), (4,0.52), (5,0.65), (6,0.78), (6.9,1), (8,1.04), (10,1.3), (30,4.6)
\end{align*}
\]

Units: Dmnl

53. Sensitivity of Conventional Oil Production to Oil Price

\[
\begin{align*}
(1,0) & - (10,4.5), (1.5,0.55), (1.2,0.6), (1.3,0.7), (1.5,0.8), (2.16,1), (3,1.3), (3.5,2), (8,3.5), (10,4.5)
\end{align*}
\]

Units: Dmnl

54. Sensitivity of Growth Rate on Remaining Countries Demand

\[
\begin{align*}
(0,0) & - (8,4), (0,0), (0.1,0.05), (0.2,0.1), (0.5,0.25), (0.8,0.4), (1,0.5), (1.5,0.75), (2.35,1), (4.2), (6,3), (8,4)
\end{align*}
\]

Units: Dmnl

55. Sensitivity of India Demand to Oil Price

\[
\begin{align*}
(20,0) & - (200,3), (20,3), (40,367,2,06579), (60,1.7), (80,1.4), (90,1.2), (100,1.1), (120,0.94), (140,0.82), (160,0.71), (180,0.6), (200,0.3)
\end{align*}
\]

Units: Dmnl
56. Sensitivity of India's Oil Demand to GDP Growth Rate\(((0,0)-(20,2.6)],(0,0),(1,0.15),(2,0.3),(3,0.45),(4,0.6),(5,0.75),(6,0.9),(7.99,1),(8,1.04),(9,1.3),(10.458,7,1.73333),(20,2.6)]\)
   Units: Dmnl

57. "Sensitivity of Non-OPEC Production Rate to Oil Price"\(((10,0.2)-(250,1.1)],(10,0.2),(20,0.5),(40,0.8),(80,0.95),(100,0.31,1),(120,1.005),(140,1.01),(160,1.01),(180,1.01)]\)
   Units: Dmnl

58. Sensitivity of OPEC Production Rate to Oil Price\(((10,0)-(250,2)],(10,0.1),(20,0.4),(30,0.7),(50,0.85),(80,0.95),(100,0.31,1),(120,1.03),(130,1.05),(150,1.08),(250,1.1)]\)
   Units: Dmnl

59. "Sensitivity of Price to Oil Demand/Supply Coverage"=0
   Units: Dmnl
   Controls the response of price to inventory coverage. Must be: negative for high inventory to lead to lower prices; higher absolute values lead to greater price changes for any given inventory coverage level.

60. Sensitivity of RC's Demand to Oil Price\(((20,0)-(200,3.6)],(20,3.6),(40,2.02),(60,1.48),(80,1.2),(90,1.1),(100,0.94),(140,0.82),(160,0.71),(180,0.6),(200,0.49)]\)
   Units: Dmnl
61. Sensitivity of Shale Oil Production to Oil Price

\[(1,0)-(10,6),(1,0.3),(1.1,0.4),(1.2,0.5),(1.5,0.75),(2.16,1),(3,1.3),(5,2.5),(10,6)\]

Units: Dmnl

62. Total Oil Demand=(China Demand+India Demand+US Demand+"Remaining Countries'(RC) Demand")*Other Factors Affecting Demand

Units: Barrels/Year

63. Total Oil Stock = INTEG (+OPEC Production Rate-Consumption Rate, Initial Oil Stock)

Units: Barrel

64. US Conventional Oil Production Rate=US Production Factor*Reference Production Rate for US Conventional Oil*Effect of Oil Price on US Conventional Oil Production

Units: Barrels/Year

65. US Demand=(IF THEN ELSE(US Oil Stock<0, (US Oil Stock) , (0.04*Total Oil Stock) ))/Demand Adjustment Time

Units: Barrels/Year

66. US Oil Consumption Factor=1

Units: Dmnl

The consumption factors is linked to the productivity of capital and is assumed exogenous and constant. One unit of capital is defined as the capital stock required to generate one unit of output per year (at normal utilization), so consumption factor =1.

67. US Oil Consumption Rate=MIN((US Oil Stock/Years of Oil Remaining),(Reference US Oil Consumption Rate*US Oil Consumption Factor))

Units: Barrels/Year

68. US Oil Stock= INTEG (US Conventional Oil Production Rate+US Shale Oil Production Rate-US Oil Consumption Rate, Reference Production Rate for US Conventional Oil+Reference Shale Oil Production Rate)

Units: Barrels

69. US Production Factor=1

Units: Dmnl

70. US Shale Oil Production Factor= 100

Units: Dmnl

71. US Shale Oil Production Rate=Reference Shale Oil Production Rate*US Shale Oil Production Factor*Price Multiplier on Shale Production

Units: Barrels/Year

72. Years of Oil Remaining= 53.3

Units: Years

The world has 53.3 years of oil left at the current rate of production, according to BP’s annual statistical review of world energy.
India Coal Power Capacity and CO2 Emission Dynamics
A2. Documentation for Coal in India model

1. Accumulated CO\textsubscript{2} Emissions= \text{INTEG (Net CO\textsubscript{2} Emissions, Init Accumulated CO\textsubscript{2} Emissions)}
   Units: Million Tonnes

2. Adjustment in Emission Reduction=(India's Desired Emission Target Level-Accumulated CO\textsubscript{2} Emissions)/timeline to meet emission targets
   Units: Million Tonnes/Year

3. Annual Increase in Subsidies=0.05
   Units: Dmnl/Year

4. Average Coal Usage Factor=0.46
   Units: Dmnl
   (IEEFA estimates coal-fired power plants to average around 45-56%.)

5. Average RC Lifetime=30
   Units: Year

6. Avg CC Lifetime=50
   Units: Year

7. Avg Clean CC Lifetime=50
   Units: Year

8. Base Year Emissions=337.89
   Units: Million Tonnes

9. Birth rate=0.01 (17.37 per 1000 people)
   Units: Dmnl/Year

10. Capacity Adjustment to Demand= ("Electricity Consumption in Capacity (MW)"-Total Potential Generation)/Capacity Adjustment to Demand Time
    Units: MW/Year

11. CC Additions=\text{MAX(0, Indicated CC Investment)}
    Units: MW/Year

12. CC Adjustment Time=3
    Units: Year

13. CC and RES share=(Total Electricity Consumption*0.9)*(kWh to MWh)
    Units: MW*hr
    Coal Capacity and RES constituted 90% of the electricity generated

14. CC Boost from Subsidies=(Subsidised Investment/Fixed Generation Cost)*Policy on coal subsidies
17. CC Completions = CC Under Construction / CC Construction Delay
   Units: MW/Year

18. CC Construction Adjustment = (Desired CC Under Construction - CC Under Construction) / CC Adjustment Time
   Units: MW/Year

19. CC Construction Delay = 4
   Units: Year

20. CC Retirements = Coal Capacity / Avg CC Lifetime
   Units: MW/Year

21. CC Under Construction = INTEG (CC Additions - CC Completions, Desired CC Under Construction)
   Units: MW

22. Change in Demand = Energy Demand * (fractional growth rate in demand + STEP input in Demand / one year * PULSE(Target Year for Demand Step, one year))
   Units: MTOE/Year

23. Change in Electricity Demand = Electricity Demand * fractional growth rate in electricity demand
   Units: MW*hr/Year

24. Change in Electricity Generation = Electricity Generated * fractional growth rate in electricity generated
   Units: TW*hr/Year

25. Clean CC Additions = MAX(0, Indicated Clean CC Investment)
   Units: MW/Year

26. Clean CC Adjustment Time = 3
   Units: Year

27. Clean CC Completions = Clean CC Under Construction / Clean CC Construction Delay
   Units: MW/Year

28. Clean CC Construction Adjustment = (Desired Clean CC Under Construction - Clean CC Under Construction) / Clean CC Adjustment Time
   Units: MW/Year

29. Clean CC Construction Delay = 4
   Units: Year

30. Clean CC Retirements = Clean Coal Capacity / Avg Clean CC Lifetime
    Units: MW/Year

31. Clean CC Under Construction = INTEG (Clean CC Additions - Clean CC Completions,
Desired Clean CC Under Construction
Units: MW

32. Clean Coal Capacity = INTEG (Clean CC Completions - Clean CC Retirements, Clean Init CC)
Units: MW

33. Clean Init CC = 0
Units: MW
(no estimated clean coal capacity in the base year)

34. CO₂ intensity of GDP = GDP/Accumulated CO₂ Emissions
Units: Million Tonnes/Billion USD

35. Coal Capacity = INTEG (CC Completions - CC Retirements, Init CC)
Units: MW

36. Coal Capacity Utilisation Factor = 0.7 [0.4-0.8]
Units: Dmnl

37. Coal CO₂ per MWh = 0.7*1e-07 1 MWh = 0.7 tonnes
Units: Million Tonnes/(MW*hr)

38. Coal Emission Factor = Coal CO₂ per MWh”hrs/year”
Units: Million Tonnes/(MW*Year)

39. Desired CC acquisition rate = CC Retirements + (Desired CC - Coal Capacity)/CC Adjustment Time + Coal Capacity*Expected demand growth rate
Units: MW/Year

40. Desired CC Under Construction = Desired CC acquisition rate*CC Construction Delay
Units: MW

41. Desired Clean CC = Desired Total CC*Desired Fraction Clean Coal
Units: MW

42. Desired Clean CC acquisition rate = Clean CC Retirements + (Desired Clean CC - Clean Coal Capacity)/Clean CC Adjustment Time + Clean Coal Capacity*Expected demand growth rate
Units: MW/Year

43. Desired Clean CC Under Construction = Desired Clean CC acquisition rate*Clean CC Construction Delay
Units: MW

44. Desired Clean Coal Frac Table = [[(2000,0), (2050,1)],(2000,0),(2010,0),(2020,0.01),(2030,0.2),(2040,0.5),(2050,0.5)]
Units: fraction

45. Desired Coal Frac Table = [[(2000,0), (2050,1)],(2000,0.8),(2010,0.8),(2020,0.6),(2030,0.5),(2040,0.5)]]
46. Desired Fraction Clean Coal = Desired Clean Coal Frac Table (Time/one year)
   Units: Dmnl

47. Desired Fraction of CC = Desired Coal Frac Table (Time/one year)
   Units: Dmnl

48. Desired Per Capita Electricity Demand = Standard Per Capita Electricity Consumption in OECO*Desired Per Capita Electricity Demand Look up (Time/one year)
   Units: hr*kW/Person

49. Desired Per Capita Electricity Demand Look up = \([(2000,0) - (2050,10)], (2000,0.5), (2010,1), (2015,1.2), (2020,1.3), (2030,2), (2050,7)]
   Units: Dmnl

50. Desired RC Fraction = Desired RC Fraction Table (Time/one year)
    Units: Dmnl

51. Desired Total CC = "Electricity Consumption in Capacity (MW)**MAX(Desired Fraction of CC, RES Shortfall Fraction)*(Pressure to Add Additional Capacity/5)
    Units: MW

52. "Electricity Consumption in Capacity (MW)" = CC and RES share/hrs in year
    Units: MW

53. Desired CC = Desired Total CC*(1-Desired Fraction Clean Coal)
    Units: MW

    Units: MW

55. Desired RC acquisition rate = RC Retirements + (Desired RC-Renewable Capacity)/time to adjust Renewable Capacity+ Renewable Capacity*Expected demand growth rate
    Units: MW/Year

56. Desired RC Fraction Table = \([(2000,0) - (2050,1)], (2000,0.001), (2010,0.12), (2020,0.23), (2050,0.4)]
    Units: fraction

57. Desired RC Under Constr = Desired RC acquisition rate*RC Construction Delay
    Units: MW

58. Effect of Electricity Demand Growth on Investment = relative electricity demand^Sensitivity of electricity demand growth on investment
    Units: Dmnl
59. Effect of Energy Demand Growth on Investment = relative energy demand^senstivity of investment of energy demand growth
   Units: Dmnl

60. Electric power consumption growth rate = Electric power consumption kWh per capita*kwh per capita growth rate
   Units: kWh per capita/Year

61. Electric power consumption kWh per capita = INTEG (electric power consumption growth rate, Init Electric power consumption kWh per capita)
   Units: kWh per capita

62. Electricity consumption per GDP = 1.89*10^9
   Units: (kW*hr)/Billion USD
   1885.52538 kWh per 1000 USD 1.9 kWh per USD 1 million thousand in 1 billion USD

63. Electricity Demand = INTEG (Change in Electricity Demand, Init Electricity Demand)
   Units: MW*hr

64. Electricity Generated = INTEG (Change in Electricity Generation, Init Electricity Generated)
   Units: kWh

65. "Electricity generated in MW*Hr from CC and RES" = Electricity Generated*0.9
   Units: MW*hr
   (Coal Capacity and RES constituted 90% of the electricity generated)

66. Electricity Demand to Capacity Conversion MW = Electricity Demand/hrs in year
   Units: MW

67. Energy Demand = INTEG (Change in Demand, Init Energy Demand)
   Units: MTOE

68. Energy Demand in MW = Energy Demand"MTOE/MW"
   Units: MW

69. Expected demand growth rate = 0.05
   Units: fraction/Year
   (Really this should be formed by observing actual growth, but since that’s not driven by an economic structure, simpler to make this a parameter.)

70. fractional growth rate in demand = 0.044
   Units: Dmnl/Year

71. fractional growth rate in electricity demand = 0.057
   Units: Dmnl/Year
   (TERI study estimated the primary energy growth rate as 4.4%/year during 1997-2019 and 3.6% during 2020-2047. For electricity the corresponding growth rates were 5.7%/year and 3.9%/year. (Source: dae.gov.in). IEO(2002) estimation: energy consumption growth rate = 3.6%/year; electricity growth rate = 3.8%/year The Royal Society and the Royal Academy of Engineers estimate 4%/year electricity growth rate for the period 1997-2012; 3%/year until
2050 and 2%/year for the rest of the century. CEA estimated electricity growth rate in India to be about 6.5%/year between 1997-2012.)

72. fractional growth rate in electricity generated=0.045  
   Units: Dmnl/Year

73. GDP= INTEG (GDP Growth,GDP init)  
   Units: Billion USD

74. GDP Growth=GDP*GDP Growth Rate  
   Units: Billion USD/Year

75. GDP Growth Rate=0.07  
   Units: Dmnl/Year

76. GDP init=468.4  
   Units: Billion USD  

77. Household electricity consumption=rural electricity consumption+urban electricity consumption  
   Units: kWhr

78. hrs in year=8760  
   Units: hr

79. India's Desired Emission Target Level=(Base Year Emissions*Target Reduction Fraction)  
   Units: Million Tonnes

80. India's Per Capita Electricity Consumption=Total Electricity Consumption/Population  
   Units: kWhr/Person

81. India's Renewable Target Gap=(Renewable Capacity Target-Renewable Capacity)/time to meet India's Renewable Target  
   Units: MW/Year

82. Indicated CC Investment=Desired CC acquisition rate+CC Construction Adjustment  
   Units: MW/Year

83. Indicated Clean CC Investment=Desired Clean CC acquisition rate+Clean CC Construction Adjustment  
   Units: MW/Year

84. Indicated Emission Red Timeline=1  
   Units: Dmnl/Year

85. Indicated investment in RC=(Desired RC acquisition rate + RC Construction Adjustment)  
   Units: MW/Year

86. Indicated Reduction in Capacity for Desired Carbon Emission Reduction=MAX(0,-(Adjustment in Emission Reduction/Coal Emission Factor))
87. Industry electricity consumption = GDP * Electricity consumption per GDP
   Units: kWh

88. Init Accumulated CO₂ Emissions = 337.89
   Units: Million Tonnes
   (The total CO₂ emission in 2000, the base year of simulation was 965.41 million tonnes. BP Statistical Review assumes that 35% (34.7%) of the CO₂ emitted from fossil fuel combustion came from electricity generation.)

89. Init CC = 62131
   Units: MW
   Reported Coal Capacity in 2000.

90. Init Electric power consumption kWh per capita = 393.646
   Units: kWh per capita
   (World Bank Estimate)

91. Init Electricity Demand = 376 * 1e+06
   Units: MW * hr
   571439 * (1000) 376 TWh: 1 TWh = 100000

92. Init Electricity Generated = 571 * 1e+09
   Units: kWh
   1TWhr = 10^9kwh

93. Init Energy Demand = 441
   Units: MTOE

94. Init Renewable Capacity = 1628
   Units: MW
   CEA estimates 1628 MW of RES at the end of 9th year plan (31.03.02). RES includes 25 MW of Hydro

95. kwh per capita growth rate = 0.052
   Units: Dmnl/Year

96. Net Change in Subsidies = Normal Government Subsidy to Support Demand Growth * Annual Increase in Subsidies
   Units: USD/(Year*Year)

97. Net CO₂ Emissions = (Coal Capacity) * Average Coal Usage Factor * Coal Emission Factor
   Units: Million Tonnes/Year

98. Net Growth Rate = Population * birth rate
   Units: Person/Year

99. Normal Government Subsidy to Support Demand Growth = INTEG (Net Change in Subsidies, Existing Subsidy)
Units: USD/Year

100. one year == 1
Units: Year

101. Per Capita Electricity Demand = "Total Potential Electricity Generated from CC+RES"/Population
Units: (MW*hr)/Person/Year

102. Policy Implementation Time = 2030
Units: Year

103. Policy on coal subsidies = Policy table(Time/one year)
Units: 1

104. POLICY SWITCH for RC Growth = 1
Units: Dmnl [0,1]

105. Policy table([[2000,0]-[2050,10]),(2000,0.5),(2015,1),(2020,1.5),(2030,1),(2050,0.5])
Units: 1

Units: Person

107. Population in 2000 = 1.057*(1e+09)
Units: Person

108. "potential coal-based generation" = total coal capacity*coal capacity utilisation factor
Units: MW

109. "potential renewable-based generation" = Renewable Capacity*renewable capacity utilisation factor
Units: MW

110. Pressure to Add Additional Capacity = (1-sensitivity to per capita consumption improvement) + sensitivity to per capita consumption improvement*Desired Per Capita Electricity Demand/India's Per Capita Electricity Consumption
Units: Dmnl

111. RC Additions = MAX(0, indicated investment in RC)
Units: MW/Year

112. RC Completions = RC Under Construction/RC Construction Delay
Units: MW/Year

113. RC Construction Adjustment = (Desired RC Under Constr - RC Under Construction)/time to adjust Renewable Capacity
Units: MW/Year

114. RC Construction Delay = 5
Units: Year
115. RC Retirements=Renewable Capacity/Average RC Lifetime  
Units: MW/Year

116. RC Share=Renewable Capacity/Total Capacity  
Units: fraction

117. RC Target Lookup Table([[0,0),(2035,400000),(2000,1628),(2022,175000),(2035,400000)])  
Units: MW

118. RC Under Construction= INTEG (RC Additions-RC Completions, Desired RC Under Constr)  
Units: MW

119. relative electricity demand=Electricity Demand/Init Electricity Demand  
Units: 1

120. relative energy demand=Energy Demand/Init Energy Demand  
Units: 1

121. Renewable Capacity= INTEG (RC Completions-RC Retirements, Init Renewable Capacity)  
Units: MW

122. renewable capacity investment timeline=1  
Units: Year

123. Renewable Capacity Target=IF THEN ELSE( Time<2022 , 175000 , Revised Target )  
Units: MW

124. renewable capacity utilisation factor=0.27  
Units: Dmnl

125. RES Shortfall Fraction=1-Desired RC Fraction  
Units: Dmnl

126. Revised Target=400000  
Units: MW

127. rural electricity consumption=rural population*rural electricity demand per capita  
Units: kWhr

128. rural electricity demand per capita=96  
Units: kWhr/Person  
World Bank

129. rural population=Population-urban population  
Units: Person

130. Sensitivity of carbon emission reduction=0.5
132. Sensitivity of electricity demand growth on investment = 0.3
Units: Dmnl

133. Sensitivity to per capita consumption improvement = 1
Units: Dmnl [0,1]

134. Sensitivity of investment of energy demand growth = 0.2
Units: Dmnl

135. Standard Per Capita Electricity Consumption in OECD = 7700
Units: kW*hr/Person
(Electric power consumption in OECD Member countries in 2014 was 7771.14 kWh per capita.)

136. STEP input in Demand = 0
Units: fraction [0,0.2]

137. Subsidies Support for RC Growth = WITH LOOKUP (Time/one year,
(((2000,0)-(2050,20)),(2000,1),(2015,11),(2030,5),(2050,1)))
Or,
(((2000,0)-(2050,10000)),(2000,1),(2005,100),(2010,2000),(2015,4000),(2023.01,6587.68),(2050,10000))
Units: Dmnl

138. Subsidised Coal = Normal Government Subsidy to Support Demand Growth * SWITCH Subsidies Growth + Existing Subsidy * (1 - SWITCH Subsidies Growth)
Units: USD/Year

139. Subsidised Investment = Subsidised Coal + Mining and other expenses
Units: USD/Year

140. SWITCH CO₂ Reduction = 0 (OFF) 1 (ON)
Units: Dmnl

141. SWITCH EFFECT of CO₂ Reduction = STEP(SWITCH CO₂ Reduction, Policy Implementation Time)
Units: Dmnl

142. SWITCH Subsidies Growth = 0 (OFF) 1 (ON)
Units: Dmnl [0,1]

143. Target Reduction Fraction = 0.3
Units: Dmnl

144. Target Year for Demand Step = 2030
Units: Year

145. Time to adjust Renewable Capacity = 2
Units: Year
146. time to meet India's Renewable Target=22
   Units: Year

147. timeline to meet emission targets=22
   Units: Year

148. Total Capacity=Coal Capacity+Renewable Capacity
   Units: MW

149. total coal capacity=Coal Capacity+Clean Coal Capacity
   Units: MW

150. Total Electricity Consumption=Household electricity consumption+Industry electricity consumption
   Units: kWhr

151. "Total Potential Electricity Generated from CC+RES"=hrs in year*Total Potential Generation
   Units: MW*hr

152. Total Potential Generation="potential coal-based generation"+"potential renewable-based generation"
   Units: MW

153. "TW*hr to MW*hr"=1e+06
   Units: MW/TW

154. urban electricity consumption=urban electricity demand per capita*urban population
   Units: kWhr

155. urban electricity demand per capita=288
   Units: kWhr/Person

156. urban population=Population*urbanisation rate
   Units: Person

157. urbanisation rate=0.34
   Units: Dimnl
Bibliography


Choucri, N., 1980. The international petroleum exchange model: Reference results and validation.. Futures, 12(3), pp. 201-211.


Clean Coal Building a Future through Technology, World Coal Institute; Available at: http://www.sacollierymanagers.org.za/docs/Clean%20Coal%20-%20Building%20%20Future%20through%20Technology.pdf


Coal, World Coal Association, Available at: https://www.worldcoal.org/coal/coal-market-pricing


Data, Energy Resources, Coal, World Energy Council 2018, Available at: https://www.worldenergy.org/data/resources/resource/coal/


Downie, C., 2015. Global energy governance: do the BRICs have the energy to drive reform?. International Affairs, 91(4), pp.799-812.


Factbox-The world's top coal trading companies, 2009, Available at: https://uk.reuters.com/article/coal-factbox-traders/factbox-the-worlds-top-coal-trading-companies-idUKLI62998020090519


Global Status Report, Global CCS Institute, Available at: https://www.globalccsinstitute.com/resources/global-status-report/


History of Convention: Essential Background, UNFCCC, Available at: https://unfccc.int/process/the-convention/history-of-the-convention#eq-1


ICIS Online: Coal Prices, markets & analysis, Available at:https://www.icis.com/explore/commodities/energy/coal/#about-coal


IRENA. (2016). THE TRUE COST OF FOSSIL FUELS:SAVING ON THE EXTERNALITIES OF AIR POLLUTION AND CLIMATE CHANGE. IRENA.


Kendall, R., Brown, T., and Hetherington, L. Mineral Profile Coal. 2010. BGS Web Publication


Kingdom of Saudi Arabi (2019), VISION 2030, [online] Available at: https://www.vision2030.gov.sa/


The Baltic Exchange, https://www.balticexchange.com/market-information/


The Paris Agreement, Process and Meetings, UNFCCC, Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

The World Coal Institute: http://www.worldcoal.org/


UN, 2017. United Nations, Department of Economic and Social Affairs, Population Division:


Van de Graaf, T., 2013. The politics and institutions of global energy governance.


