Energy Supply Chain Design:

Future Energy Security of Pakistan

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A dissertation submitted to the

Graduate School-Newark

Rutgers, The State University of New Jersey

in partial fulfillment of requirements

for the degree of

Doctor of Philosophy

Graduate Program in Management

Written under the direction of

Dr. Yao Zhao

and approved by

Newark, New Jersey

May, 2015

ABSTRACT OF THE THESIS

Essays on Energy Supply Chain

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In recent years, Pakistan is suffering 25-40% shortfall of electricity supply nationwide that stagnated the country's economic growth and resulted into political turmoil and social instability. The energy deficiency is especially ironic to the fact that Pakistan has huge untapped coal reserves which can be used to cope with the energy needs of the country for next few centuries.

We study the development of a vast infrastructure, namely, the energy supply chain (network), currently non-existent in Pakistan. Such an infrastructure or network connects coal reserves with demand zones by generating and transmitting electricity from coal-fired power plants but it requires a significant investment. However, Pakistan is in heavy debts and its financial status only allows limited investment for the energy sector, which leads to a vicious cycle that revolves around energy deficiency, economic slow-down and a lack of investment in energy sector. The objective of this thesis is to find a strategic plan that builds up energy infrastructure (mines, rail systems, power plants, transmission network) dynamically in an optimal and sustainable way by taking into account the interaction between energy gaps and economic growth so that the total energy gap is minimized.

Part 1 of this dissertation presents an overview of energy supply chain, literature review along with detailed study of different settings of power plants and demand zones under static environment to understand trade-offs and develop insights among key players of energy supply chain. The heuristics developed in this part explain the structural properties of our problem to optimally build up a dynamic energy supply chain efficiently.

In Part 2 of this study, we develop an optimization-based mathematical model that quantifies the interplay of various variables and trade-offs, and determines which reserve(s) to be mined and where to locate the power plants strategically over time so as to reduce the energy gap as fast as the meager budget allows. Specifically, the mathematical model aims at designing a strategic plan that builds up energy infrastructure (mines, rail systems, power plants, transmission network) dynamically in an optimal and sustainable way by taking into account the interaction between energy gaps and economic growth. For various time horizons (25 or 50 years) and investment plans as a percentage of annual GDP, we show that the optimal solution reduces energy gap and improves net GDP (total GDP less investment in energy sector) much faster than the government plan.

In Part 3, sustainability aspects that include economic, environmental and social dimensions of current energy supply chain are discussed. Economic analysis focused on key issues related to diversity of energy supplies, availability, affordability, continuity of supply and vulnerability to foreign threats. EIO-LCA (economic input output life cycle assessment) approach is used to analyze the impact of GHG emissions on environment from electricity generation through coal. Finally, social dimension is discussed with the aid of ecological system theory.

This work can be extended in several directions. First, the mathematical model developed for coal resources can be extended to other energy resources such as oil, gas and hydro, etc. to address similar issues. Second, characterizing the mathematical properties of energy supply chain for more efficient solution algorithms can be another extension of this research. Finally, an energy portfolio for optimal energy mix can be the next-level of complexity to answer in future studies.

Acknowledgments

I thank to Almighty Allah, most Gracious, who in His infinite mercy has guided me to complete this PhD work. May Peace and Blessings of Allah be upon His Prophet Muhammad (peace be upon him).

I would like to express my sincere gratitude to my adviser Prof. Yao Zhao for the continuous support of my Ph.D study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me throughout this research. I could not have imagined having a better adviser and mentor for my Ph.D study. I am also grateful to Prof. Kevin Lyons for his advice, knowledge and many insightful discussions and suggestions.

Besides my advisers, I would like to thank the rest of my committee members; Prof. Endre Boros, Prof. Larry Snyder and Prof. Weiwei Chen for their encouragement, insightful comments, and hard questions.

My friends in US, Pakistan and other parts of the world were sources of laughter, joy, and support. Special thanks go to KwonGi Mun for his help and support during tough times in my research. I would also like to thank Steven Carnovale, Abdullah Aldousari, Andika Pratama and Yijun Wang for being best colleagues during this journey. I am very happy that, in many cases, my friendship with you have extended well beyond our shared time at RBS.

I gratefully acknowledge U.S. State Department and IIE for the funding that made my Ph.D work possible. I was funded by Fulbright Scholarship for my entire Ph.D program.

It is an honor to be a part of elite group of *Fulbright scholars*. Thanks a lot *Senator Fulbright* for your vision.

A special thanks to my family. I wish to thank my parents as their love and prayers provided me inspiration and was my driving force. I owe them everything. I would like to thank my wife who stood by me through good and bad times. Lots of love to my kids, Hania and Muhammad, for cheering me up. Finally, I would like to dedicate this work to my parents especially to my late Father whose memories were always with me during my Ph.D studies. I hope that this work will make him proud.

Dedicated to my Parents

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Chapter 1

Introduction

1.1 Background

Pakistan is facing severe electricity crises of all time since its inception in 1947. The country's already struggling economy has found itself in a state of economic and social turmoil that is posing a serious threat to national security environment (Kugelman, 2013). According to government official sources, PEPCO (Pakistan Electric Power Company) electricity shortfall in summer-2012 increased to 6,000 MWh whereas the demand was estimated at 15,000 MWh and supply at just 9,000 MWh. It was the same story in summer of 2013, when the electricity shortages have peaked at 6,500 MWh with an estimated demand standing at 16,500 MWh and a supply at 10,000 MWh. According to NEPRA (National Electric Power Regulatory Authority, 2012), some rural areas have been experiencing unscheduled load shedding and lengthy blackout sessions up to 16-18 hrs a day, while in cities load shedding increased to 8-12 hours a day. It is estimated that these shortages have cost around 2-4% of GDP annually during the past few years.

As a result, there is a sharp rise in unemployment due to closure of hundreds of industrial units all over the country. Production capacity of some key industries (textile and fertilizer sectors) has fallen to nearly 50%-60%. Riots due to anger over long and unscheduled electricity load shedding are common which result in clashes between police and protesters. Life in cities and urban areas paralyzed as protesters block roads and demonstrate sit-ins in front of government offices. There is a widespread damage to several government offices and few causalities are reported due to these clashes. As mentioned by Kugelman (2013), in February 2013 Pakistan's minister for water and power warned that the energy crisis has become a national security issue.

The energy deficiency in last few years have put many industrial sectors of Pakistan on the verge of collapse. The high inflation and unemployment rate is pushing millions of people into poverty. For example, Faisalabad, the third-largest city in Pakistan with a population of about 2.6 million inhabitants and well known for its textiles, is affected badly due to power shortages. Textile Exporters Association estimated that about 150,000 jobs were lost in Faisalabad and surrounding Punjab province over the last five years (Santana, 2013). Consequently, the political, social and industrial infrastructures of Pakistan are crumbling.

One of main causes for the energy crises of the country is the poor energy mix over last few years. According to IEA (International Energy Agency, 2011) and NEPRA (National Electric Power Regulatory Authority, 2012) Pakistan's electricity mix is heavily dependent on thermal resources, such as oil (contributed 38.2%) and gas (25.4%), in comparison to the 5% world's average for electricity generation through oil. Coal made only a negligible contribution (0.2%) to the total energy supplied in Pakistan. The heavy dependence on imported oil and gas for power generation is risky and pricey due to the highly volatile prices of oil in the global market. As described by Malik (2008), with the volatility of the oil prices, over dependence on oil and utilization of depleting gas reserves, the current energy mix is not sustainable to secure energy future of Pakistan.

Management and maintenance failure of transmission and distribution infrastructure is another major problem preventing Pakistan from recovering the energy crises. Officially reported estimates of 2009-10 transmission and distribution yield losses are around 22%, way higher than other Asian countries, such as Korea 3.6%, China 8% and OECD countries below 7% (Malik 2012).

Pakistan has the 5th largest coal reserve (mostly untapped) in the world with approximately 185 billion tons of coal, equivalent to about 300 billion barrels of oil, which exceeds the combined oil reserves of Saudi Arabia and Iran. By IEA (International Energy Agency, 2011), we note that global average for electricity generation with coal is 41%. As mentioned by Malik (2010), increasing reliance on coal for power generation instead of imported oil is a necessary step towards resolving the energy crises. Therefore, given the grievous situation that Pakistan economy is facing, it seems that aggressive utilization of coal reserves for a better balance in the energy mix is perhaps the only option for long-term energy security of Pakistan.

The dilemma faced by the Pakistan is that while it is bestowed with huge natural coal reserves labeled as "Black Gold", the country is in heavy debts, and thus unable to finance projects to utilize coal reserves. In order to introduce energy policy reforms and develop energy infrastructure based on coal, Pakistan needs significant capital investment; however, with the current debts and credit rating, it is hard for the government to raise such funds.

Such large-scale infrastructure projects take years to fruition and hence international donors are reluctant to commit further funds without strong reforms from Pakistan's political leadership. To change the financial condition of the country, Pakistan needs to grow its economy. However, without energy, economic growth is just unfeasible. The vicious cycle (*Figure 1.1*) that revolves around energy deficiency, economic recession and lack of investment for the energy sector led Pakistan into a downward economic spiral and worsened the crisis.

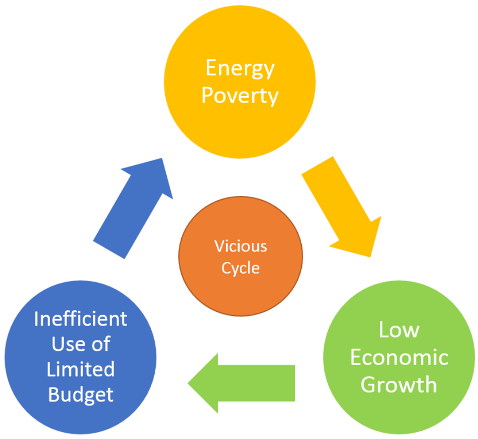


Figure 1.1: The Vicious cycle

Pakistan does not stand alone in its energy crisis as the same challenge and vicious cycle are faced by many developing countries around the world, especially those in sub-Saharan Africa. The case of Pakistan, however, is complicated by a rapidly growing population and thus a fast increasing demand for energy. Pakistan, currently with about

180 million people, is estimated to require 1000 megawatts per year to meet the country's electricity needs (Walsh and Masood, 2013).

The tasks of breaking the vicious cycle and steering Pakistan into an upward economic spiral are formidable and require persistent structural reforms in the energy sector by the government, and creative strategies for developing the energy supply chain around coal resources to address both the immediate and long-term needs.

Realizing the potential of coal, Pakistan government formulated a plan to shift its energy mix from imported oil and depleting gas reserves towards indigenous coal resources. Government outlined a strategy to develop Thar coal fields (largest coal reserves with 175 billion tons of coal) to solve energy crisis in the country. For past few year, federal and provincial governments (Sindh province) allocated annual budgets for the project.

As of today, the project is still primitive in terms of infrastructure development of Thar coal mines. According to government plan, Thar coal mines will be used for electricity generation by building coal fired power plants at mines and electricity will be transmitted using transmission network from coal mines to the rest of the country. As per government plan there would be benefits of having several projects in close proximity to Thar, as transmission grid facilities could be shared by the different projects.

However, even after two decades (1993-2013), there has been no significant development towards the electricity generation through these coal reserves. In the past, there are few minor efforts of developing other medium sized coal reserves located in Sindh province (Sonda and Lakhra coal fields) but none of them were successful in long run.

1.2 Energy Supply Chain

A coal-fired energy supply chain includes the following major components: coal mines, railway network, power plants, transmission network and demand zones (*see Figure 1.2*). The railway network transports coal from the mines to power plants, and the transmission network transmits electricity from power plants to demand zones.

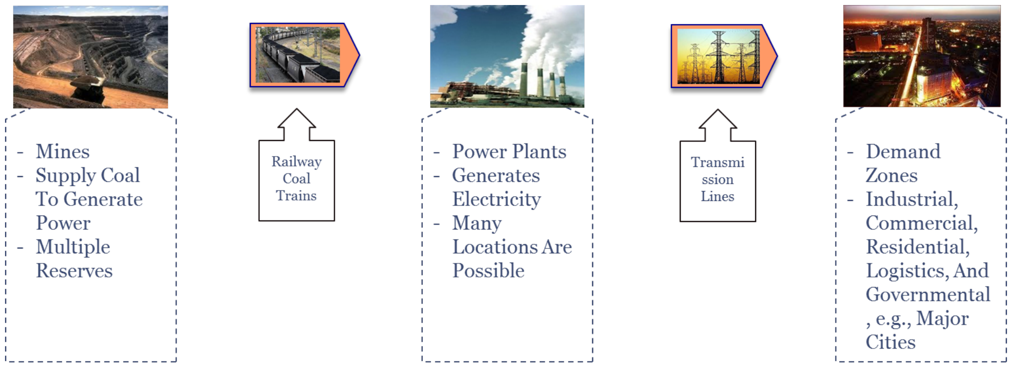


Figure 1.2: Coal-based energy supply chain

It is not clear how to build up a coal-fired energy supply chain for Pakistan because of the complex network and the unique features/economies of energy supply chains. Pakistan has two provinces that contributed significantly to the country's economy: Punjab province (the industrial center contributing 60% GDP) in the north and Sindh province (the commercial center contributing 20% of GDP) in the south (*see Figure 1.3*). Punjab (or Sindh) account for about 60-75% (20%, respectively) of the country's total power consumption. Geographically, major cities of these two provinces scatter across more than half of the country's area with a distance between Lahore (the capital city of Punjab) and Karachi (the capital city of Sindh) about 800 miles.

Pakistan has three main coal reserves which account for approximately 98% of the country's total coal reserves (*Figure 1.3*); Thar, Sonda/Lakhra and Salt Range. Thar, the largest reserve (essentially unlimited), is located in a desert far away from major demand zones. To get Thar ready for mining, a significant amount of infrastructure must be built which will cost at least $6 billion and take 5 years. The medium reserve at Sonda/Lakhra is near the demand zones in Sindh and would cost $2 billion and take 3 years to be ready. Salt Range, located in a close proximity to Punjab, is the smallest and barely enough for 10-15 years, but only costs $0.5 billion and takes less than 3 years to be ready.

Figure 1.3: Pakistan coal reserves and major GDP provinces.
Soruce: Modified from "Nations Online Project".

Geographically dispersed demand zones and reserves (large and small) pose a significant challenge in deciding which reserve(s) to mine, where to locate power plants, and where to build the railway and transmission lines. Specifically, the fact that the larger reserves are closer to the smaller demand zones (Sindh) in the south and the smallest reserve is closer to the larger demand zones (Punjab) in the north makes such decisions intriguing and requires a delicate balance among the driving forces in the coal-fired energy supply chain.

An energy supply chain is an integrated system where decisions on one part may affect other parts. For example, if PPs are placed near mines but farther away from demand zones, railway cost for coal transportation will be lower but the yield loss will be higher and so more PPs must be built. Conversely, if PPs are placed near demand zones, then yield loss will be lower but the railway cost will be higher. Defining coal-transportation related costs as inbound costs and transmission-yield induced costs as outbound costs, an effective design of energy supply chains requires a delicate balance of the *trade-off* between inbound and outbound costs. This can be a substantial challenge because (1) an energy supply chain is a complex network with geographically dispersed demand zones and reserves, (2) an energy supply system is dynamic in nature due to the limited reserves, fast growing demand, and the causal relationship between energy consumption, GDP and budget.

The driving forces are determined by the unique economics of an energy supply chain. Specifically, a standard 300 MWh power plant requires 2,000 tons of coal every day to run at its full capacity which places heavy loads on the railway network. The railway cost includes a fixed construction cost of railway track at an average of $13 million per mile, a cost of coal train which is approximately $50 million each, and a cost of coal transportation through railway network.

Power transmission line is cheaper in construction and operation than railway, but it is subject to yield losses. According to EIA (U.S. Energy Information Administration), the electricity transmission and distribution losses average about 6% per 100 miles in United States. World Bank data reports that transmission and distribution losses in Pakistan are around 20-25% due to aging infrastructure. Based on these numbers, we estimate an average of 8% yield loss per 100 miles for new or upgraded transmission lines in Pakistan. The yield loss essentially makes the energy supply chain a "leaking" supply chain. Finally, some reserves are quite limited and thus may run out during a planning horizon.

The government's plan of mining only Thar coal and building all PPs at the mine is quite intuitive because it saves railway cost and reduce waste for smaller reserves(s) that may run out. However, this plan raises two concerns: (1) the accumulated yield loss of power transmission amounts to nearly 50% over the 800-mile distance. Despite savings from railway, we have to double the number of power plants to get the same output at the end. (2) The distant largest reserve at Thar is least developed and requires ample time, approximately five years, and huge investment to explore.

While cost is an important factor in designing energy supply chains, time is equally critical. Giving the fact that Pakistan's economy is on the verge of collapse, a timely influx of new energy will not only save the country from bankruptcy but could also jump start the economy, which in turn allows more budget to be allocated to the energy sector in the future.

An energy supply chain has many unique features that distinguish it from the well-studied material supply chains (i.e., logistics networks).

1. *A material supply chain deals with production, distribution and transportation of physical goods. In contrast, a large part of an energy supply chain deals with energy generation and transmission.*

2. *Yield loss of power transmission makes an energy supply chain "leaky" while a material supply chain holds material conservation. Thus a longer distance in material supply chains leads to a higher transportation cost, but a longer distance in power transmission means that more power plants need to be built (and more coal to be burnt) to meet the same demand.*

3. *Coal reserves (the source of energy) are limited and may run out. However, factories and warehouses in a material supply chain can run for indefinite times.*

4. *Energy consumption has a strong impact on GDP, which may affect the budget for energy system development and in turn energy consumption. This dynamic feedback loop is likely much weaker in many material supply chains.*

1.3 Objective and Thesis Structure

The objective of this research is to determine the optimal way to build up energy supply chain strategically under limited budgets for energy security, economic prosperity and environmental sustainability.

The mathematical model is required to minimize the total discounted energy gap among all demand zones over a given planning horizon. Energy gaps are defined as the differences between projected demand and available supplies. The discounted factors represent less importance for a more distant year into the future.

To design an energy supply chain, we shall make decisions on reserve selection (which reserves to mine and when), the number of power plants (PPs) and their locations, rail and power transmission networks over time. In this study, we shall consider all key players of coal based energy supply chain, such as the major (three) coal reserves that represent about 98% of total coal reserves of the country, the major (19) demand zones that represent the country's most important industrial, political and commercial regions, and (22) potential locations for power plants. The central questions are: *which reserve to mine? Where to locate the power plants? Which reserve serves which power plant? And which power plant serves which demand zone?*

In sustainability study, we shall analyze the key concerns related to coal utilization that directly affects the environment and draw criticism on coal usage for electricity generation. The integrated framework of sustainability that addresses social, economic and environmental aspects shall be discussed in context of Pakistan energy crises. The identification of key energy indicators of sustainable energy supply chain can provide guidelines to policymakers for future energy security of Pakistan.

The dissertation is structured as follows; *Chapter-2* provides an overview of country's current energy supply chain by explaining electricity generation resources, existing infrastructure issues, financial status and energy demand outlook. The chapter is concluded with a detailed information about coal reserves and government plan for these reserves.

In *Chapter-3*, a comprehensive literature review related to two broad streams of literature: the design of material supply chains, such as logistics networks and integrated supply chains; and energy economics and policy is presented. Furthermore, we conducted a static analysis of energy supply chain to understand the importance of location of PPs and demand zones across the country. The heuristics developed in static environment emphasized the importance of trade-off between coal transportation cost and transmission yield loss. Moreover, the significance of dispersed demand zones identified as a key aspect of energy supply chain. Substantial cost savings are observed when there is flexibility in the location of power plants for multiple scattered demand zones.

As mentioned earlier, government plan outlines the use of Thar coal mines only, to develop energy supply chain. Heuristics developed in this chapter helped us to analyze government plan. Contrary to government plan, our analysis confirm that the use of multiple coal mines is more economical as compared to single coal mine.

In *Chapter-4*, we extended our static model approach to accommodate the dynamic features of energy supply chain. We developed a novel class of network optimization models for dynamic energy supply chains. We run the model on real-life data collected from publicly available sources and government agencies. The data included infrastructure cost and time for each mine, major and minor demand zones in Pakistan (account for 85-90% of demand), coal transportation railway network and costs, cost for the electricity transmission and grid stations. The mathematical model is solved by a mixed-integer-linear-programming approach over a period of 25 or 50 years with an annual investment plan of 3%, 5% or 7% of GDP. The solutions are tested and analyzed for their performance on energy gap and cumulative GDP as compared to the government's plan.

The solution, obtained from mathematical model, is drastically different from the government plan. While government considers only the largest Thar reserve that is not only remote but also has the highest infrastructure cost and takes the longest time for development, our solution starts with the smallest coal reserves near country's economic centers that require much less time and capital to set up. Doing so will grow the economy faster, which, in turn, will lead to more investment back to the energy sector, and allow us to mine the Thar reserve ultimately. The power plants are scattered around the country strategically so as to minimize the transmission yield loss (and thus requires fewer power plants) at an affordable coal transportation cost by considering, in advance, a potential supply switching from the smallest reserves (after they are depleted) to Thar reserve.

In *Chapter-5*, a detailed study of economic, environmental and social dimensions is presented to address key issues and challenges faced in the development of sustainable energy supply chain. Diversity of energy supplies, availability, affordability, continuity of supply and vulnerability to foreign threats are identified as main economic indicators in context of Pakistan energy crisis. In environmental analysis, EIO-LCA (economic input output life cycle assessment) approach analyzed the environmental impact of CO_2 emissions. Coal mining and electricity (power) generation sector are identified as major contributors to GHG emissions. Environmental section is concluded with few recommendations regarding GHG emission control and an emphasis on advanced technology and balance energy mix for electricity generation through coal.

Bronfenbrenner's ecological theory is used to analyze social impact of energy crisis. Social dimension is considered a neglected area in sustainability literature in general. The theoretical approach helped authors to explain the social dimension by analyzing the interaction of government's policy decisions (the macrosystem), the role of administrative units (the exosystem) and the tension that exists between mesosystem and exosystems.

The dissertation is finally concluded in *Chapter-6* with a brief summary and possible future extensions of our research.

Chapter 2

Pakistan Energy Supply Chain

2.1 Electricity Generation Resources

Pakistan electricity generation is heavily dependent on thermal resources (oil & gas) along with a fluctuating share of hydro resources in electricity generation. A brief description of available resources along with possible potential for electricity generation is discussed in the following sections.

2.1.1 Hydroelectric Sector

The seasonal variations of reservoir levels and consequent fluctuation in power output of storage type hydel dams in Pakistan are very pronounced. According to WAPDA (Water Resources & Power Development Authority, 2009), Tarbela Dam has a maximum head of 450 feet and experiences a variation of 230 feet; Mangla Dam has a maximum head of 360 feet and experiences a variation of 162 feet. During the lean flow (low head) period of

Tarbela Dam from November to June, the power output reduces to as low as 1,350 MW against the maximum output of 3,692 MW during the heavy flow (high head) period from August to September every year. Lean flow period of Mangla Dam is from October to March when the minimum generating capability is 500 MW. The capability rises to as high as 1,150 MW during high head period (15% permissible overloading). In summary, Water and Power Development Authority (WAPDA) hydel generating capability varies between the two extremes of 2,414 MW and 6,746 MW in a year.

The main problem in the utilization of this resource is the geographical location of the Pakistani rivers – as most of them flow from disputed territory of Indian Kashmir. The construction of dams on these rivers by India has resulted in decreased flow of water into the Pakistan territory. The huge capital investment and lengthy construction time associated with hydel projects posit problems for the weak economy of the country. For example, the planned Kalabagh Dam (2,400 MW to 3,600 MW) would require $15 Billion USD and estimated 8 to 10 years to complete. Keeping in mind the poor economic condition and the immediate need for electricity, this resource does not seem to be a viable option to meet the immediate energy requirements of Pakistan.

2.1.2 Natural Gas Sector

The bulk of Pakistan's power generation comes from thermal power plants burning natural gas and oil. The total installed capacity of thermal power plants in the country is 13,296 MW. As per HDIP (Hydrocarbon Development Institute of Pakistan, 2013), the share of thermal power generation during 2012-2013 was around 67 percent. Pakistan has a well-developed and integrated infrastructure for transmission and distribution of natural gas (one of Pakistan's success stories). This sub-sector is generally open to the private sector.

Pakistan's gas reserves are 282 trillion cubic feet and current production is 4 billion cubic feet per day. There are indications of additional reserves of 35 trillion cubic feet in tight/difficult gas. The medium term (by 2014-15) decline in production of the seven largest gas fields (that account for 65% of the current total production) and their huge long-term decline (by 2019-20) represent a failure to attract more investment in gas exploration and production. As a result, it is difficult to maintain a production plateau between 4,500 and 5,000 MMcfd of gas.

Not much has been done to realize the tight gas potential and no real incentives have been provided to exploration and production companies. With the current exploration cost of gas, it is not economically feasible to burn this energy source to produce electricity (*Figure 2.1*). In addition, gas system losses are increasing due to the aging network. On the other hand, gas demand is currently growing at an 8.5% annual rate. Thus, the gas deficit is increasing as production falls significantly behind demand. Due to the increasing gas shortages, there is rationing of piped gas in winter months.

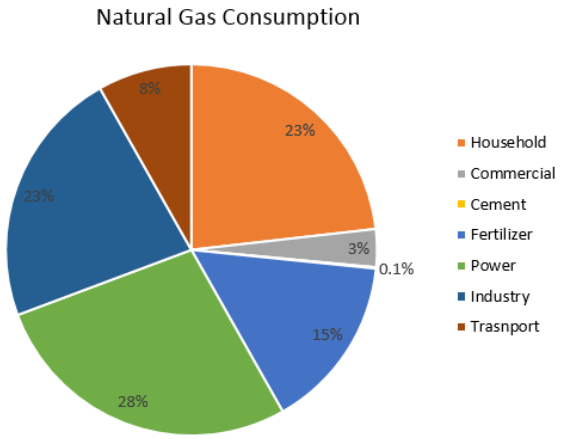


Figure 2.1: Natural gas consumption

2.1.3 Petroleum Sector

Pakistan's fuels sector leans heavily on two main fuels which account for 84% of consumption, i.e. high-speed diesel (49%) mainly used for transportation and fuel oil (41%) primarily consumed in the power sector (*Figure 2.2*).

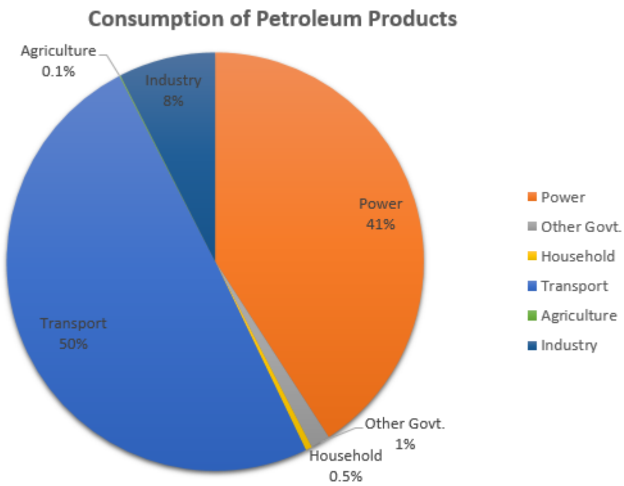


Figure 2.2: Petroleum products consumption

Pakistani ports cannot receive the large vessels deployed by oil suppliers; therefore, freight costs for delivered products and crude oil are high. Up country distribution is by road tankers, rail, and pipeline. Pakistan has a pipeline network of over 2,000 km (PARCO network) for the upcountry movement of crude oil and oil products which is an economic means of transportation. However, owing to limited capacity (1.2 million tons/yrs), considerable upcountry fuel oil movement takes place on road tankers (over 4 million tons/year, or 100,000 40-ton trucks for long-distance hauls) which is the most expensive mode of oil transportation.

There is no formal policy on managing strategic oil stocks, and thus operational stocks sometimes fall to critically low levels. One key impediment is the lack of institutional capacity for developing logistics infrastructure and linking it with oil and energy development plans. The major issue in electricity generation with fuel is the fluctuating oil prices in international market. Due to the limited domestic reserve, lack of transportation infrastructure and price volatility this resource can hardly be used as a reliable and economically viable source of electricity.

2.1.4 Nuclear Energy

Pakistan Atomic Energy Commission (PAEC) is responsible for planning, construction and operation of Karachi nuclear power plant (KANUPP) and Chashma nuclear power plant (unit-1 & unit-2). The construction of two more units is in progress.

KANUPP, located at Karachi, completed its design life of 30 years in 2002. After necessary refurbishments and safety retrofits, it is now operating on extended life. KANUPP, generated highest ever electricity in a calendar year in 2012, in its 40-years history. C-1 and C-2 located at Chashma are also performing well. C-1 achieved record of continuous operation of 239.13 days in July 2012. Performance of the operating nuclear power plants of Pakistan is shown in *Table: 2.1*.

Performance of Operating Nuclear Plants in Pakistan	
Plants	**Gross Capacity(MW)**
KANUPP	137
C-1	325
C-2	325

Table 2.1: Nuclear energy

The commercial operation of the under construction nuclear power plants C-3 and C-4 of 340 MW each, is planned in December 2016 and October 2017, respectively. The government has mandated Pakistan Atomic Energy Commission (PAEC) for the installation of 8,800 MW nuclear power capacities by the year 2030.

PAEC has technical and engineering infrastructure in place to provide technical support to existing under construction and future nuclear power plants. It also has a network of in-house educational and training institutions that encompass all major facets of nuclear science and technology.

2.1.5 Renewable Energy

Pakistan has abundant and inexhaustible renewable energy resources, such as wind and solar power, which, if tapped effectively, can play a considerable role in contributing towards energy security and energy independence of the country. In May 2003, Alternative Energy Development Board (AEDB) was established to act as a central agency for development, promotion and facilitation of renewable energy technologies, formulation of plans, policies and development of a technological base for manufacturing of renewable energy equipment in Pakistan (*Table: 2.2*).

Renewable Energy Potential in Pakistan	
Wind	0.346 Million MW
Solar	2.9 Million MW

Table 2.2: Renewable energy

Government of Pakistan has tasked the AEDB to ensure that renewable energy technologies can produce 5% of total national power generation capacity by year 2030. At present, the total renewable energy produced in the country is 40 MW which accounts for about 0.21% of total installed generation capacity of all sorts. The investment requirement for the renewable energy sector of the country from short to medium term is over 16 billion USD which is not feasible under current financial circumstances.

2.2 Energy Supply Chain Infrastructure

The available logistics network infrastructure for fuel transportation and electricity transmission in the existing energy supply chain is discussed below:

2.2.1 Railway Network

Railway network is considered as the most cost effective method of fuel (oil, coal) transportation. The initial cost of fuel transportation is normally high but fuels can be transported over a long distance through a dedicated network that makes this network more economical as compared to other options available. Rail services are provided by the state-run Pakistan railways, under the supervision of the ministry of railways. Pakistan railways provides an important mode of transportation catering to the large-scale movement of people and freight.

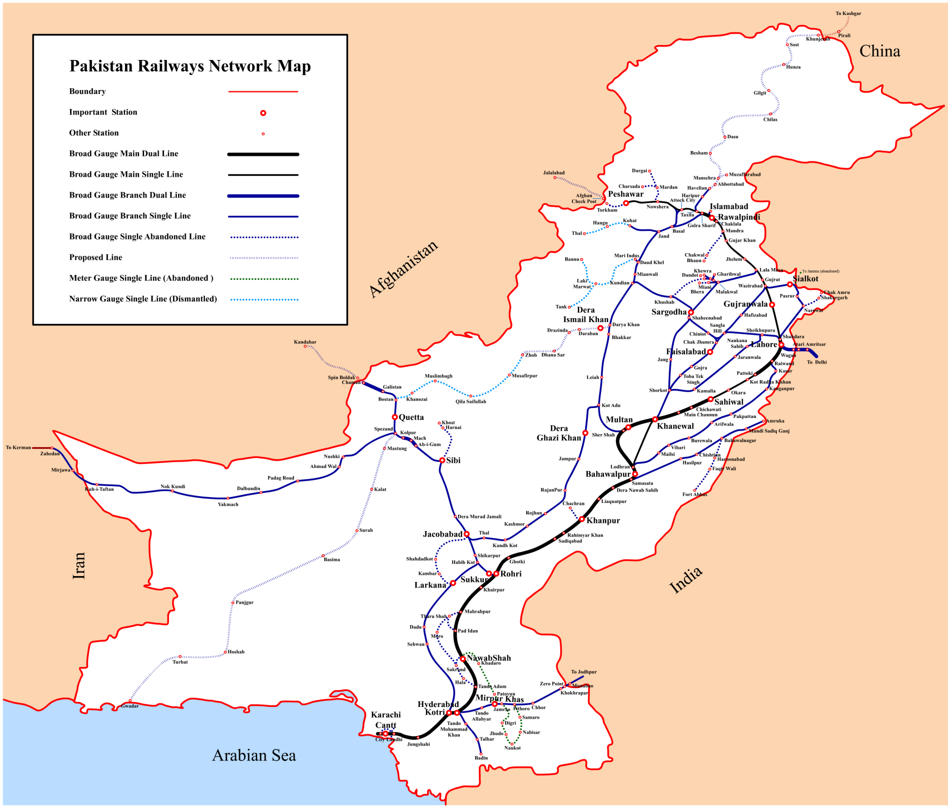


Figure 2.3: Pakistan railways network. Adopted from “Pakistan Railways Network Map” by Adnanrail Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons.

Railway network has a total length of 8,163 km, of which 7,718 km are 1,676 mm (5 ft 6 in) broad gauge tracks, including 293 km of electrified track, and the remaining 445 km are 1,000 mm (3 ft 3 in) narrow gauge tracks. Earning from passenger rail service comprise of approximately 50% of the total revenue. Pakistan Railways carry 65 million passengers annually and daily operate 228 mails, express and passenger trains. Pakistan railways also operate special trains for various occasions.

The Freight Business Unit (FBU) with 12,000 personnel operates over 200 freight stations on the railway network. The FBU serves the Port of Karachi and Port Qasim as well as various other stations along the network and generates revenue from the movement of agricultural, industrial and imported products such as wheat, coal, fertilizer, cement, and sugar. About 39% of the revenue is generated from the transportation of petroleum, 19% from imported wheat, fertilizer and rock phosphate. The remaining 42% is earned from domestic traffic. The freight rates structure is based on market trends in road transport which is the main competitor to rail transport. Rail-transported coal is typically moved in unit trains that operate in dedicated shuttle service between a mine and a destination.

2.2.2 Highway Network

Highway network plays an important role in energy supply for fuels transported through road network with large trucks within the range of 100-120 km. For distances more than 120 km, cost of transportation increases substantially and is not economically feasible. The construction of motorways began in the early 1990s with the idea of building a world class road network and reducing the load off the heavily used national highways throughout the country. Meanwhile all the national highways were rebuild during 1990's to connect important financial, cargo and textile centers.

National Highway Authority (NHA) is responsible for the maintenance of all national highways in Pakistan. Truck transportation is used to move coal instead of a water or rail carrier or for direct shipment to the customer. Trucks have the advantage of routing flexibility and modest capital requirements, but for fuel like coal, it can be economically transported for at most about 120 km due to the high unit cost of moving a low-value product in relatively small batches. Coal-carrying vehicles are typically end-dump trucks with a carrying capacity of roughly 25 to 50 tons depending on local road conditions and safety regulations.

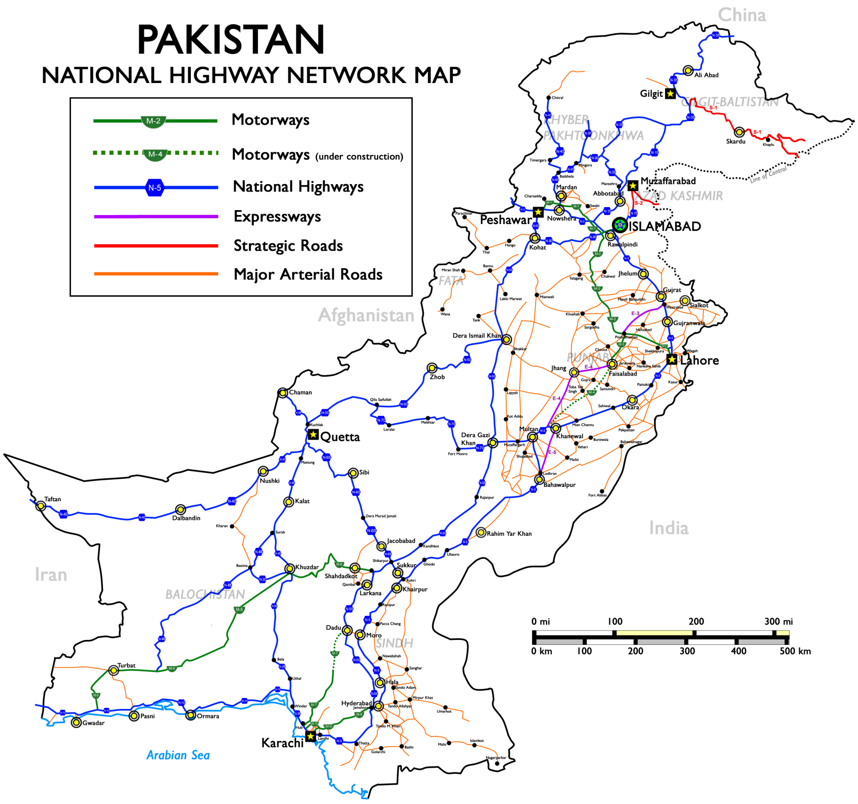


Figure 2.4: Pakistan highways network. Adopted from "Pakistan National Highways" by Nomi887 Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons.

2.2.3 Pipeline Network

The pipeline network of Pakistan is comprised of two gas marketing companies, Sui Northern Gas Pipeline Limited (SNGPL) and Sui Southern Gas Company Limited (SS-GCL), and one crude oil-cum-product pipeline company (PARCO). The total natural gas infrastructure network comprises 10,740 kilometers (km) of transmission lines and 101,733 km of distribution lines with the appropriate compression facilities designed to achieve system efficiency.

SNGPL transmission system extends from Sui in Balochistan to Peshawar in the NWFP comprising over 7,016 km of transmission system (main lines and loop lines). SNGPL's transmission and distribution system extends from Sui in Baluchistan to Peshawar in Khyber-Pakhtunkw passing through Punjab, and accounts for 1788 million cubic feet per day (MMcfd), or 48% of total gas in the country.

Sui Southern Gas Company system is over 3,080 km including (main lines and loop lines). SSGCL operates in the southern part of the country (Baluchistan and Sindh) and accounts for 1,157 MMcfd or 30% of total gas in the country. The rest (22%) of the gas supply is transported via independent systems. Parco operates a network of crude oil-cum-product pipelines running over 2,000 kilometers across the country.

2.2.4 Transmission Network

In Pakistan, two companies are engaged in electric power transmission; they are National Transmission and Dispatch Company (NTDC) and Karachi Electric Supply Company Limited (KESC). NTDC is the national grid company of Pakistan and is exclusively responsible for electric power transmission for the entire country except the area covered by KESC.

- *National Transmission and Dispatch Company (NTDC):* NTDC is responsible for overall reliability, planning and coordination of the electricity transmission in Pakistan except the area under KESC. NTDC is a public sector company and came into existence as a result of restructuring of WAPDA in 1998 and obtained a transmission license from National Electric Power Regulatory Authority in 2002 to engage in the exclusive transmission business for a term of thirty years.

- *Karachi Electric Supply Company Limited (KESC):* The second company engaged in electric power transmission business in Pakistan is KESC. It has two separate licenses; electric generation and distribution, while its application for a transmission license is currently under consideration by NEPRA.

As a result of restructuring and unbundling of the power of Water and Power Development Authority (WAPDA), DISCOs are responsible for channeling electricity to the transmission substations. The end users are classified as residential, commercial, industrial, agriculture and street lights etc.

Overall, the distribution system, especially in an urban area, is over stressed and needs to be upgraded, augmented and expanded. Besides these distribution companies, Karachi Electric Supply Company (KESC) is a private limited company and is engaged in distribution of electric power in the area of Karachi. In addition to one private and nine public distribution companies, National Power Regulatory Authority (NEPRA) has so far granted seven distribution licenses to small power producers (SPPs) for supply of electric power to designated bulk power consumers.

2.3 Energy Supply Chain Issues

2.3.1 Energy Mix

Pakistan's electricity generation capacity is heavily dependent on thermal sources including gas and oil. The contribution of oil and natural gas towards the energy mix is around 38.2% and 25.4% respectively. There is only a minor contribution of coal (0.2%) toward electricity generation (*Figure 2.5*).

Pakistan's lack of diversification in energy mix is among one of the main reason for electricity shortages. Countries like United States, China and India rely heavily on coal for electricity generation with coal share for electricity generation around 22%, 45% and 67% respectively describes the importance of coal in power generation infrastructure.

Pakistan is not self sufficient in oil reserves and as a result oil imported for energy purposed increases the cost of electricity. Imported energy ranges around 30% of Pakistan total energy generation and is increasing each year for past few years. Oil dependance for electricity generation is linked with the scarcity of the available resources of water and gas.

In early 1980s, the energy generation of Pakistan was chiefly dependent on water resources (40-45%). The gradual decline of water bed in Pakistan along with the seasonality factor (the availability of hydro resource varies from 10% to 30% in a year) resulted in a shift from hydro to natural gas. Natural gas resource, found in 1952, was established as a major contributor for electricity ever since. But in recent years, the natural gas resources are depleting and thus cannot meet the increasing demand of the country. Compressed natural gas stations are facing weekly closures due to the scarcity of gas. Along with the electricity load shedding, domestic consumers are also face gas load shedding in the winter months. The shortage of natural gas contributes to another reason towards the policy shift on fossil fuels to generate electricity.

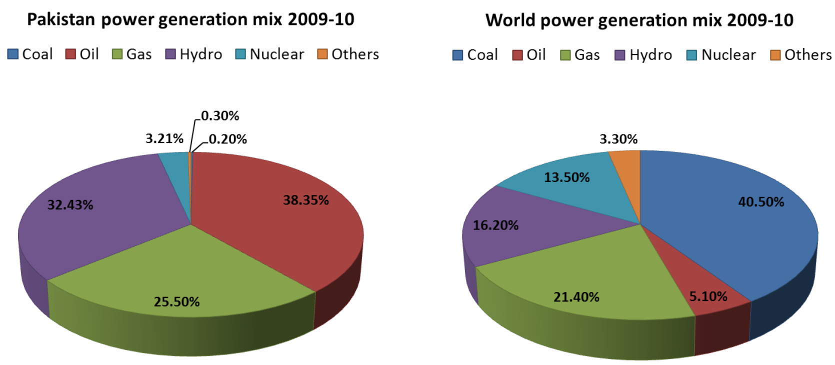


Figure 2.5: Energy mix comparison

As shown in *Figure 2.5*, share of coal for electricity generation is only 0.2%. With the availability of huge coal reserves which are ranked as 5th largest coal reserves in the world it is quite obvious how power crises challenge should be addressed. It is highly recommended by the experts, that government should shift energy policy from expensive oil to cheap coal reserves.

Dr. Atta ur Rahman, one of Pakistan's leading scientists urged strongly on importance of coal for electricity generation by stating that *"Coal should be given the highest national priority to meet our energy needs"*.

Dr. Adil Najam, Professor, Earth & Environment, Boston University, Lead Author for the Intergovernmental Panel on Climate Change (IPCC) work for which the IPCC was awarded the 2007 Nobel Peace Prize along with Al Gore, stated: *"We are in a bind and I know coal can never be clean; we have been forced to make difficult decisions but perhaps the saving grace can be to make the cleanest decisions possible, such as using relatively cleaner technologies and how we use and conserve energy we produce."*

2.3.2 Efficiency Losses:

Pakistan's industry is energy inefficient. This is attributable to high energy losses, waste throughout the energy supply chain, and inadequate investment in replacing obsolete infrastructure. For each dollar of GDP, Pakistan uses 15% more energy than India and 25% more than the Philippines.

According to World Bank (2012) power sector experiences *transmission and distribution losses* averaging around 20-25%. These losses are substantial and raise the cost of electricity and contribute to shortages. There can be potentially dramatic gains in supply from improving energy efficiency. Pakistan's total energy savings potential is estimated at 11.16 MTOE. Savings from energy efficiency could reach 18% of total energy consumed in the country. This corresponds to a 51% reduction in net oil imports. According to the National Energy Conservation Centre (ENERCON), annual energy savings of up to 25% are possible in all sectors which translate into approximately $3 billion in savings annually.

2.3.3 Circular Debt & Regulatory Issues:

There is a lack of uniform regulation in the energy sector that creates distortions between the gas and electricity sectors. Inconsistent regulations between the National Electric Power Regulatory Authority (NEPRA) responsible for the power sector and the Oil and Gas Regulatory Authority (OGRA) responsible for the oil and gas sectors creates a bad impression on investors and a lack of uniform pricing strategy between gas and electricity.

Major issues related to circular debt are due to a lack of good governance, inability of government/sectorial entities to effectively lay down policies/procedures and then enforce them. Government agencies often implement their current procedures and methodologies without considering their impact on circular debt. The current fuel cost reference and adjustment mechanisms does not keep up the pace with changing oil prices of international market. There is a huge concern related to theft and utility bill collection that adds on extra burden and volume on the system.

As mentioned above, poor efficiency and transmission and distribution losses are due to poor performance of distribution and transmission companies has turned this circular debt into a gigantic snowball. The government has been reluctant to introduce initiatives for the improvements in billing recovery system, theft protection and political interference in energy sector. As mentioned in planning commission report (The Causes and Impacts of Power Sector Circular Debt in Pakistan, 2013), the problem of circular debt is not impossible to overcome if the sector's governance is improved. Legacy payments can be wiped out through decisions/reconciliation of bills, arrears can be reduced to the number of days of billing cycle through strict compliance with electricity agreements, and TDS can be curtailed by charging the cost of supply of electricity to end users and targeting subsidies to deserving customers.

2.3.4 Tariff Structure:

Government of Pakistan froze tariffs between 2003 and 2007 at a very low level. The subsequent tariff increase in the following years did not make up for the shortfall while crude oil and gas prices were increasing globally. Even now the notified electricity tariffs by the government are below the cost-recovery level.

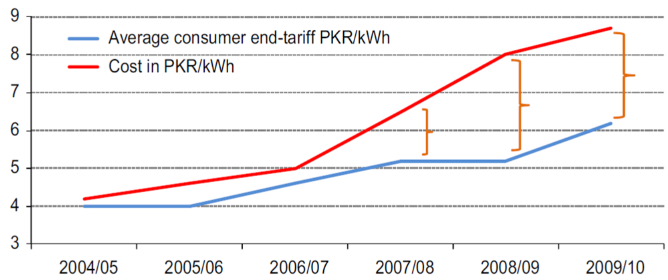


Figure 2.6: Gap between cost of service and retail price

Between FY 2004-2008, the price of imported furnace oil, which represents about one third of the fuel mix for power generation, increased by 76%. Gas prices have increased by 78% over FY 2004-05 levels. High technical and commercial losses of DISCOs also led to the increased cost of service. The government provided a tariff differential subsidy (TDS) to DISCOs to cover the gap between the cost of service tariff as determined by NEPRA and the notified uniform tariff. As shown in *Figure 2.6*, the size and growth of the cost of electricity subsidies and the growing gap between the cost of service and the level of subsidy between FY2004-05 and FY2009-10 the government's notified uniform tariff is for each customer class set at a rate that is lower than the lowest NEPRA determined tariffs of all eight DISCOs.

Ali and Badar (2010) mentioned insufficient tariffs structure to cover the rising cost of power generation and poor financial condition of the government to compensate PEPCO as a result of increasing gap between cost of service and retail price.

2.4 Pakistan Economy

According to World Bank economy of Pakistan is the 44^{th} largest in the world in nominal terms with GDP of $240 billion (2012) and 27^{th} with GDP of $514 billion (2012) largest in the world in terms of purchasing power parity (PPP). Pakistan has a semi-industrialized economy, which mainly encompasses textiles, chemicals, food processing and agriculture industries. Pakistan is classified as a developing country with the sixth largest population of 183 million (2012) in the world and a population growth rate of 3.7% (2012). Pakistan was a very poor country at the time of independence in 1947 and relied heavily on its agricultural sector. Although it has been growing ever since, the Pakistan economy has been characterized as unstable, low growth and very vulnerable to external as well as internal factors.

From 2005-2007 there was a steady economic growth at a rate from 6.1%-6.6%. This unexpected growth was the beginning of an energy crisis era because the government was unprepared for the rising demand of the energy. The result was that in the following years, Pakistan's manufacturing sector faced a double digit cut in its growth rate due to the energy shortage.

According to the HDI (Human Development Index), 60.3% of Pakistan's population lives on under \$2 a day. More and more people are pushed below the poverty line every year with unemployment at 5.6% (World Bank, 2012). According to World Bank figures debt of the country is around 62% of GDP. Pakistan's sixty-six years of political history is quite volatile and revolves around Indo-Pak wars and overthrow of the civil governments by the military rule. Factors that adversely affected the economy of Pakistan are the Asian financial crisis and post 9/11 military action in Afghanistan, political war between parties, earthquake (2005), floods (2010-11), and on-going war against terrorism which resulted in loss of 40,000 lives and damage of \$100 billion (approx.).

2.4.1 Economic Hubs

Pakistan has five provinces: Punjab, Sindh, KPK, Gilgit–Baltistan and Balochistan, as well as some administrative units including Islamabad capital territory, Federally Administered Tribal Areas (FATA) and Azad Kashmir *Figure 2.7.* The growth poles of Pakistan's economy are situated along the Indus River, where diversified economies of Sindh and Punjab's urban centers coexist with lesser developed areas. The major economic hubs of Pakistan economy are discussed in more detail in following sections.

- *Punjab Province:* Punjab province has 56% of the national population (170 million) and is the hub of the industrial and agriculture sectors. Punjab is the most industrialized province of Pakistan; its manufacturing industries produce textiles, sporting goods, heavy machinery, electrical appliances, surgical instruments, cement, vehicles, auto parts, metals, rickshaws, floor coverings, and processed foods. The major industrial cities are Lahore, Faisalabad, Gujranwala, Gujrat, Sialkot, Sheikhupura and Multan. The province manufactures approximately 90% of the paper and paper boards, 71% of fertilizers, 69% of sugar and 40% of cement in Pakistan. Punjab contributes about 76% to annual food grain production in the country.

Figure 2.7: Pakistan economic mainstay map

Punjab province contributes 55% towards total population (183 million) is the hub of industrial and agriculture sectors. Punjab is the most industrialized province of Pakistan; its manufacturing industries produce textiles, sporting goods, heavy machinery, electrical appliances, surgical instruments, cement, vehicles, auto parts, metals, rickshaws, floor coverings, and processed foods. The major industrial cities are Lahore, Faisalabad, Gujranwala, Gujrat, Sialkot, Sheikhupura and Multan. The province manufactures approximately 90% of the paper and paper boards, 71% of fertilizers, 69% of sugar and 40% of cement in Pakistan. Punjab contributes about 76% to annual food grain production in the country. Punjab also has more than 68,000 industrial units, including 39,033 small and cottage industrial units, and 14,820 textile units.

Cities like Lahore, Faisalabad and Gujranwala have the largest concentration of small light engineering units. Faisalabad is know for a strong textile industrial base. The textile industry of Faisalabad constitutes more than 20% of the textile export of Pakistan. This makes Faisalabad share of the total exports from Pakistan more than 15%.

The district of Sialkot excels in sporting goods, surgical instruments and cutlery goods. Punjab has always contributed the most to the national economy of Pakistan. Its share of Pakistan's GDP is around 60% as of 2012. It is especially dominant in the service and agriculture sectors of Pakistan economy. With its contribution ranging from 52.1% to 64.5% in the Service Sector and 56.1% to 61.5% in the Agriculture Sector, it is the major manpower contributor because it has the largest pool of professionals and highly skilled (technically trained) manpower in Pakistan. It is also dominant in the manufacturing sector with historical contributions ranging from a low of 44% to a high of 52.6%. In 2010, Punjab achieved a growth rate of 6% against the total GDP growth of Pakistan at 4.3% (Economy of Punjab, Pakistan. n.d.).

- *Sindh Province:* Sindh province has the second highest Human Development Index out of Pakistan's four provinces at 0.628. Main cities include Karachi, Sukkur, Mirpukhas, Nawabshah, Umerkot and Larkana. With an estimated population of 15 million, Karachi is the most populous city in the country. It is Pakistan's premier center of banking, industrial, economic activity and trade. It is the home to Pakistan's largest corporations, including those in textiles, shipping, automotive industry, entertainment, arts, fashion, advertising, publishing, software development and medical research.

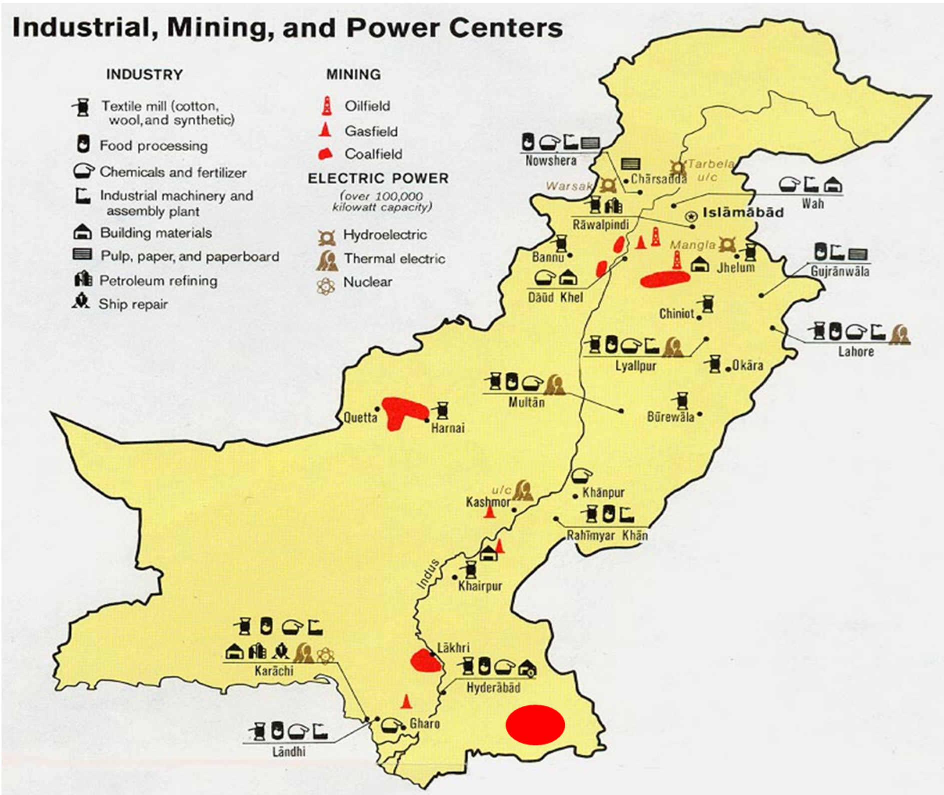


Figure 2.8: Pakistan industrial, mining centers. Source: NationMaster.com

Karachi is the financial and commercial capital of Pakistan. In line with its status as a major port and the country's largest metropolis, it accounts for a lion's share of Pakistan's economy. Karachi's contribution to Pakistan's manufacturing sector is approximately 30%. A substantial part of Sindh's gross domestic product (GDP) is attributed to Karachi – the GDP of Sindh as a percentage of Pakistan's total GDP has traditionally hovered around 28%-30%, Karachi's GDP is around 20% of the total GDP of Pakistan.

According to Water-house Coopers study released in 2009, which surveyed the 2008 GDP of the top cities in the world, calculated Karachi's GDP (PPP) to be $78 billion (projected to be $193 billion in 2025 at a growth rate of 5.5%). Karachi's high GDP is based on its mega-industrial base, with a high dependency on the financial sector. Textiles, cement, steel, heavy machinery, chemicals, food, banking and insurance are also the major segments contributing to Karachi's GDP. In February 2007, the World Bank identified Karachi as the most business-friendly city in Pakistan. Karachi has several large industrial zones. Its primary areas of industry are textiles, pharmaceutical, steel, and automobiles. In addition, Karachi has a vibrant cottage industry and there is a rapidly flourishing free zone with an annual growth rate of nearly 6.5%.

2.5 Energy Demand Outlook

According to IPP (Institute of Public Policy; 2009, 2010) the cost of load shedding in industrial sector had a huge impact on industrial sector. The cost to the industrial sector was 157 billion rupees and the cost to vale added sectors was additionally 53 billion rupees making a total of 210 billion rupees that is valued around 2% of GDP. Moreover, around 400,000 workers lost their jobs due to reduction in export orders by international firms as a result of power outages.

The total loss to the exports for year 2009 was around $1 billion. The situation became worst in year 2009 and the cost to the industrial sector climbed to 230 billion rupees. The cost to other sectors also increased from Rs. 53 billion to Rs. 95 billion. The cost of industrial load shedding increased from Rs. 210 billion in 2008 to Rs. 325 billion i.e. from 2% to 2.5% of GDP. The industrial sector witnessed all time high unemployment figures increasing from last year estimates of 400,000 to 535,000 workers.

National Costs of Electricity Loadshedding		
	2008	2009
Cost to the industrial sector	Rs. 157 billion	Rs. 230 billion
Cost to the other sectors of industrial loss of value added	Rs. 53 billion	Rs. 95 billion
Total cost of industrial loadshedding to the economy	Rs. 210 billion	Rs. 325 billion
Cost as % of GDP	2	2.5
Loss of employment in the economy	4,000,000	535,000
Loss of exports	$ 1 billion	$ 1.3 billion

Table 2.3: National costs of loadshedding

The reason behind this catastrophic situation in energy sector is the the growth pattern of the demand. Due to the lack of planning and clear policy how to cope these growing needs for the country, now the difference between demand and supply has widened and energy gap is increasing exponentially. As noted by IPP (Institute of Public Policy,

2010) growth rates for demand and supply for past few decades show the pattern how the installed capacity decreased over time (*Table: 2.4*). Pasha (1989) mentioned reasons behind this demand growth which includes increase in domestic growth for electricity averaging over 21% per year during 1980 and around 10% during past decades

Growth Rates of Electricity Demand & Supply (ACGR%)			
	Demand	Supply	
		Installed Capacity	Generation
1972-1980	8.6	8.3	8.9
1981-1990	10.9	6.8	9.9
1991-2000	4.2	8.5	5.4
2001-2008	6.1	1.5	5

Table 2.4: Demand supply % growth

Other factors include growth in agriculture, manufacturing and service sectors along with government plans to electrify rural areas. The problem exacerbated by subsidized tariffs which had declined 24% in real terms during 1980s. In 2001-2008, energy demand was increasing around 6% with GDP around 6.6% in 2006-2007, economy was struck with power shortages resulting worst power crises in the history of the country.

According to USAID (United States Agency for International Development, 2010), electricity shortfall become significant in 2005-2006 (*Table: 2.5*) and economic growth suffered due to electricity loadshedding. Government tried to compensate the industrial sector by long unscheduled loadshedding hours and blackouts for domestic consumers. The situation became worst with every coming year along with a decline in economic growth.

The electricity outages not only block the economic growth but also push more population into poverty that breeds extremism and violence in society. At a time when the country is fighting a war against terrorism the deterioration in security conditions has compounded the problems in the energy sector. Private investment in the energy sector has dwindled. Public investment has fallen as development spending is substituted by increasing military spending to finance the war against terrorism.

Demand and corresponding generation capacity (MW)			
Fiscal Year	Computed Peak Demand	Supply	Surplus\shortfall
2001-02	10,459	10,894	435
2002-03	11,044	10,958	-86
2003-04	11,598	11,834	236
2004-05	12,595	12,792	197
2005-06	13,847	12,600	-1247
2006-07	15,838	13,292	-2546
2007-08	17,398	12,442	-4956
2008-09	17,852	13,637	-4215
2009-10	18,467	13,445	-5022

Table 2.5: Demand and Power Generation Capacity

2.6 Pakistan Coal Reserves and Government's Plan

Pakistan has approximately 185 billion tons of coal reserves (see *Table: 2.6*), most of which remain untapped. Pakistan's Coal reservoirs exceed the combined oil reserves of Saudi Arabia and Iran. The worth of these 185 billion tons of coal reserves are estimated as $25 trillion. According to the experts this much quantity of coal can be use to generate 50,000 megawatts of electricity for 500 years. It would not only cater to the electricity requirements of the country for next several decades, but would also help reduce the oil import bill by USD 4-4.50 billion annually and help Forex reserves.

Pakistan Coal Reserves		
Province	**Reserves** (Million Tons)	**How much is this coal?**
Sindh	184,623	Worth of USD 25 trillion.
Balochistan	217	Exceeds combined oil reserves of Sadui Arabia and Iran.
Punjab	213	50,000 MW of electricity can be produced for 500 years.
KPK	91	Or, 100 million barrel diesel for 500 years.
AJK	9	
Total	**185,175**	

Table 2.6: Pakistan coal reserves

As shown in *Figure 2.9*, major coal reserves are located in Sindh province. Although Punjab province has 235 million tons of coal reserves, yet these coal reserves alone are not enough to satisfy the ever increasing demand of manufacturing and agricultural hub of country. Punjab province is the most populous province of Pakistan with 65% of the electricity demand originates from this province. On the other hand, demand for electricity of Sindh province is around 20% but the coal reserves near Sindh are far more enough for the whole country for next few centuries.

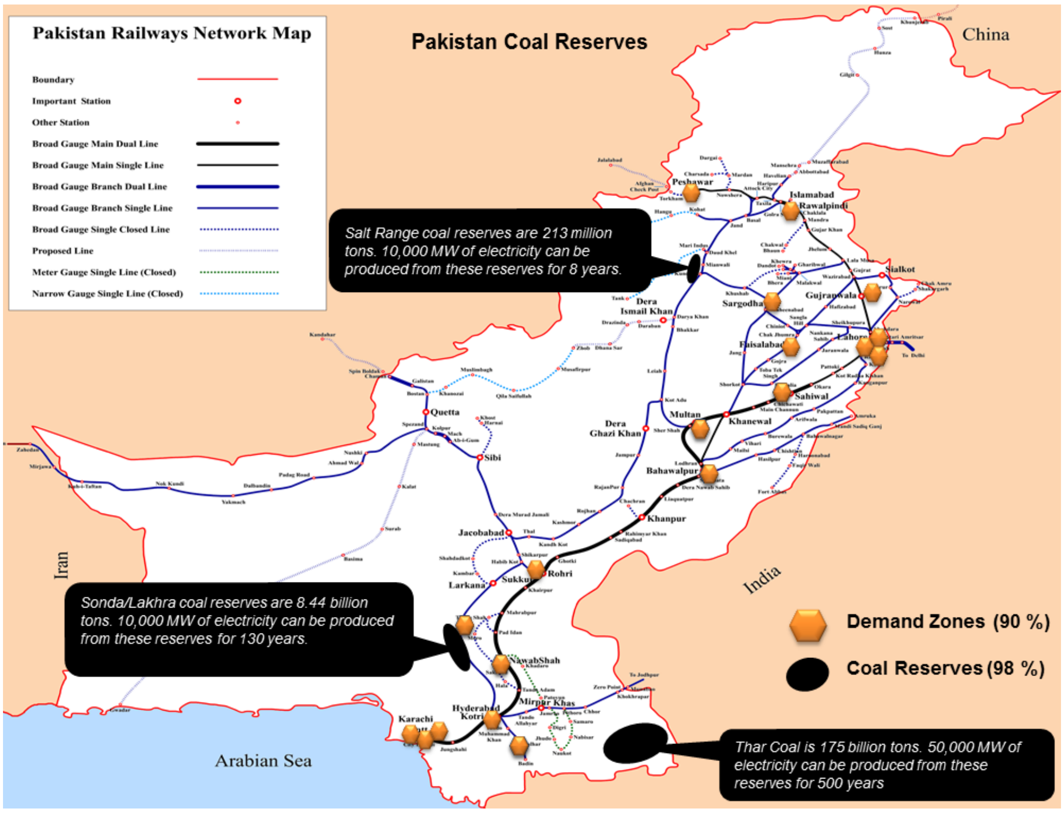


Figure 2.9: Coal reserves map

Realizing the potential of coal, the Pakistan government is shifting its energy mix from imported oil and dwindling gas reserves to coal. There has been a long history and many efforts of developing the Thar, Sonda and Lakhra coal fields, but none of them were successful. The existing situation of the Sindh and Punjab coal fields is described below.

2.6.1 Sonda Coal Field:

The Sonda coalfield was discovered by Geological Survery of Pakistan (GSP) and United States Geological Survey in 1981. The drilling data indicates that the coal bed is about 6.2 meters thick and the over burden is about 120 meters at the first mineable seam. The total coal reserves are estimated to be 7,773 million tonnes.

Sonda Coal Reserves	
Moisture (%)	9.0 - 48.0
Ash (%)	2.7 - 52.0
Volatile Matter (%)	16.1 - 44.2
Fixed Carbon (%)	8.9 - 58.8
Sulfur (%)	0.2 - 15.0
Calorific Value (Btu\lb)	5,219 - 13,555
The quality of coal is Lignite-A	
Coal Reserves (Million Tonnes)	
Measured	245
Indicated	1,611
Inferred	5,917
Total	**7,773**

Table 2.7: Sonda Coal Reserves, Source: NEPRA, 2004

The feasibility study of Sonda coal is yet to be initiated. The coal reserves and chemical analysis of coal samples are shown in *Table: 2.7.* Few companies showed interest in power project using Sonda coal filed but unfortunately these companies abandoned their projects due to disputed tariffs and the lack of interest of the government in developing the required mining infrastructure.

2.6.2 Lakhra Coal Field:

After the first discovery of coal in 1853, as aforesaid, many geological investigations have been conducted in the Lakhra area by national and international organizations. Interests in large-scale exploration of coal for power generation began to develop in the early 1960s when Geological Survery of Pakistan (GSP) and United States Geological Survey (USGS) performed a systematic geological investigation of the area. West Pakistan Industrial Development Corporation (WPIDC) tests found Lakhra coal unsuited for hard coke production, but suitable for power generation. In 1996, WPIDC engaged a Polish firm to undertake a mining and power generation feasibility study on Lakhra coal (Ebinger and Kessler, 1985).

In 1978, Japan International Cooperation Agency (JICA) carried out additional technical, financial and economical feasibility studies. In 1981, JICA reported positive results and concluded that a 300 MW plant was technically feasible, but estimated the coal production cost to be very high. Then Government of Pakistan (GOP) asked United States Agency for International Development (USAID) to review all studies on Lakhra and make recommendations on the technical and economical feasibility of a coal-fired power station. USAID completed its Lakhra feasibility study by 1986 and confirmed JICA's appraisal, but proposed changes in design of the plant lowering the estimated cost.

Lakhra Coal Reserves	
Moisture (%)	9.7 - 38.1
Ash (%)	4.3 - 49.0
Volatile Matter (%)	18.3 - 38.6
Fixed Carbon (%)	9.8 - 38.2
Sulfur (%)	1.2 - 14.8
Calorific Value (Btu\lb)	5,503 - 9,158
The quality of coal is Lignite-A	
Coal Reserves (Million Tonnes)	
Measured	244
Indicated	629
Inferred	455
Total	**1,328**

Table 2.8: Lakhra Coal Reserves, Source: NEPRA, 2004

The USAID feasibility study concluded that a Lakhra coal mine, supplying coal for a 2 x 250 MW units power plant, was technically sound and socially and environmentally feasible. The Lakhra coalfield is connected by road through the Indus Highway and a rail track is also available near Khanot, which is also located on the Indus Highway. The Lakhra coalfield is at a distance of 50 km. from Hyderabad and 175 km. from Karachi. According to NEPRA (National Electric Power Regulatory Authority, 2004), total coal resources of Lakhra are estimated at 1,328 million tonnes. The coal reserves and chemical analysis of coal samples (dry basis) are shown in *Table: 2.8.*

2.6.3 Thar Coal Field:

Thar coal fields (*Table: 2.9*) are 410 km east of the city of Karachi. These fields are located in the desert without any established infrastructure.The government has a plan to develop the Thar coal fields to solve the energy crisis once and for all by building coal fired power plants at Thar. The power generated at Thar will be transmitted through a transmission network to the rest of the country. The plan is primitive in terms of allocation of resources and the development of infrastructure. From government's point of view, there are benefits to having several projects in close proximity to Thar, as grid facilities could be shared by the different projects.

Thar Coal Reserves	
Moisture (%)	29.6 - 55.5
Ash (%)	2.9 - 11.5
Volatile Matter (%)	23.1 - 36.6
Fixed Carbon (%)	14.2 - 34.0
Sulfur (%)	0.4 - 2.9
Calorific Value (Btu\lb)	
As received	6,244 - 11,045
Dry Basis	10,723 - 11,353
The quality of coal is Lignite-A to Lignite-B	
Coal Reserves (Million Tonnes)	
Measured	2,700
Indicated	9,395
Inferred	50,706
Hypothetical	112,705
Total	**175,506**

Table 2.9: Thar Coal Reserves, Source: NEPRA, 2004

Also the usage of ground water by several projects will lower the water table in the region, making coal mining more easy and cost effective. The possibility of using one mine service facility will be helpful for all mines and power plants and common location/-facilities for all power plants in the complex. The estimated infrastructure development cost to connect Thar coal field with the outside networks is around 1.74 billion USD, including water, electricity transmission, road network, railways link, effluent disposal systems etc. The details for the development plan for Thar are as follows:

- Construction of canal water carrier with capacity of 300 cusecs.
- Construction of 50 cusecs drainage and waste water effluent channel from mining area of Thar coal field.

- Improvement and widening of road network from seaport Karachi to Thar coalfields (360 km).
- Transmission line setup to Thar coalfields: National Transmission and Dispatch Company (NTDC), with the support of ADB (Agricultural Development Bank) funding, has initiated a feasibility study for constructing a 1300 km electricity transmission line from Thar coalfields to upcountry load centers for dispersal of 2500-3000 MW power. The process/configuration of a transmission system (including line/grid/switching station) will cater for the evacuation of at least 10,000 MW of power, and can be replicated for an additional 10,000 MW. Total estimated funding required for the transmission line is approximately 1 billion USD and the estimated construction period is 5-10 years.
- Establishment of broad-gauge railway link to Thar coalfield areas.

2.6.4 Salt Range/ Makerwal Coal Fields:

The Salt-Range coalfield covers an area of about 260 sq. km between Khushab, Dandot and Khewra in the Sargodha and Jhelum Districts of Punjab. The total reserves of the Salt-Range coal are approximately 213 million tonnes. There are more than two coal seams present in the Salt-Range but, in most cases, only one is mineable which varies in thickness from 0.3 m to 1.5 m with an average thickness of 0.75 m. According to NEPRA (National Electric Power Regulatory Authority, 2004) the coal quality is Sub-bituminous and is suitable for power generation. Coal quantity and quality of coal reserves are shown in *Table: 2.10.*

Salt Range Coal Reserves	
Moisture (%)	3.2 - 10.8
Ash (%)	12.3 - 44.2
Volatile Matter (%)	21.5 - 38.8
Fixed Carbon (%)	25.70 - 44.8
Sulfur (%)	2.60 - 10.7
Calorific Value (Btu\lb)	9,472 - 15,801
The quality of coal is Sub-bituminous	
Coal Reserves (Million Tonnes)	
Measured	50
Indicated	16
Inferred	147
Total	**213**

Table 2.10: Salt Range Coal Reserves, Source: NEPRA, 2004

The Makarwal coalfield is located in the Mianwali District of Punjab. It covers an area of about 75 km, situated near Makarwal town and 13 km west of Kalabagh. The Makarwal coalfield is connected with the Mari Indus-Bannu narrow gauge railway line. The coal occurs in the steeply dipping Hangu Formation and the thickness of its bed ranges from 0.5 to 2.0 m. The coal resources have been reported to about 22 million tonnes of Sub-bituminous type of coal(NEPRA, 2004). Because of limited reserves at Makarwal coal field (only 22 million tonnes), these reserves are not considered in this research.

Chapter 3

Literature Review & Static Analysis

In this chapter, a detailed review of literature is presented that includes two broad streams of literature: the design of material supply chains, such as logistics networks and integrated supply chains; and energy economics and policy.

Furthermore, a computational study of different settings of coal mines and demand zones is also conducted under static settings in order to understand the relationship and importance of location of mines and demand zones across the country. The heuristics developed here provide insights on how to optimally build up a coal energy supply chain efficiently.

These settings of mines and demand zones are discussed in detail from *Model-1* to *Model-4* in *section 3.3*. In *Model-1*, single source (Thar) and single demand zone (Punjab) configuration is analyzed. In *Model-2*, the setting is modified from single demand zone (Punjab) to two demand zones (Punjab and Sindh). From *Model-2* to *Model-3*, configuration is updated with the flexibility of building power plants at multiple (two) locations with all other settings being the same. *Model-4* configuration further extends our analysis from one coal mine to two coal sources (Thar and Salt Range) along with two demand zones (Punjab and Sindh).

This chapter is organized as follow; literature review is presented in *section 3.1* followed by static analysis and assumptions in *section 3.2*. Mathematical models are discussed in detail in *section 3.3*. The chapter is finally concluded with a brief summary of results presented in *section 3.4*.

3.1 Literature Review

This work is related to two broad streams of literature: the design of material supply chains, such as logistics networks and integrated supply chains; and energy economics and policy. We shall review related work in both streams and point out the contribution of this work.

3.1.1 Design of Material Supply Chains

Facility location decisions play a critical role in the strategic design of material supply chains, such as logistics networks and integrated supply chains of physical goods. A key question answered by the literature is where to locate plants, warehouses and other facilities in a material supply chain either for a single period or over multiple periods.

For instance, Geoffrion and Graves (1974) studies the optimal location of intermediate distribution facilities between plants and customers. A multi-commodity capacitated single-period version of this problem is formulated as a mixed integer linear program and solved by Benders Decomposition. Pirkul and Jayaraman (1996) develops a mixed integer programming model for a multi-commodity and multi-echelon distribution system with the objective of minimizing the transportation and distribution costs as well as the fixed costs for opening and operating the facilities. The model is solved by Lagrangian relaxation and a heuristic. The literature went beyond distribution systems to more integrated supply chains with both production/logistics and inventory (safety-stock) costs. For instance, Daskin, Coullard and Shen (2002) consider a distribution-center location model which explicitly incorporates safety-stock costs and economies of scale in transportation. The model is formulated as a non-linear integer-programming problem and solved by a Lagrangian relaxation algorithm. Shen, Coullard and Daskin (2003) studies a joint location-inventory problem where some retailers can serve as distribution centers to achieve risk pooling effect. The problem is formulated as a set-covering integer-programming model and solved by column generation algorithms. We refer the reader to Daskin, Snyder and Berger (2005), and Shen (2007) for reviews of the literature. Shu, Teo and Shen (2005) studies the stochastic transportation-inventory network design problem involving one supplier and multiple retailers, and show that by exploiting certain structures, the problem can be solved efficiently. Snyder (2006) surveys the literature of stochastic and robust facility location models.

Wesolowsky (1973) starts the dynamic facility location literature by studying the single facility location problem that permits location changes for a multi-period planning horizon. An algorithm is developed to optimize the sequence of locations in order to meet changes in cost, volume and location of destinations. Wesolowsky and Truscott (1975) extends this model to locate multiple facilities among many possible sites to serve different demand zones. Van Roy and Erlenkotter (1982) solves a capacitated dynamic location problem with opening and closing decisions using a dual-based branch-and-bound procedure. Love, Morris, and Wesolowsky (1988) provides an early review of this literature.

Hinojosa, Puerto and Fernandez (2000) studies a mixed integer programming model to build facilities at multiple echelons of a distribution system over time. A dynamic, multiple objective, mixed-integer programming model is developed by Melachrinoudis and Min (2000) to solve the multi-period relocation problem. More related work can be found in Canel and Khumawala (1997, 2001) which solve a multi-period international facilities location problem, Klose and Drexl (2005) which addresses concerns like *which customers should be serviced from which facility (or facilities)*, Troncoso and Garrido (2005) consider specific production and logistics issues in the forest industry, and Dias, Captivo, and Climaco (2007) which solves a dynamic location problem with opening, closure and reopening of facilities by primal-dual heuristic approach.

The dynamic facility location literature also considers integrated supply chains with both production/logistics and inventory issues. For instance, Gen and Syarif (2005) studies an optimization model to integrate facility location decisions with inventory management for multiple products and multiple time periods. Meixell and Gargeya (2005) reviews decision support models for global supply chain design and connects the research literature to practical issues. Altiparmak, Gen, Lin and Paksoy (2006) proposes a solution procedure based on genetic algorithms to find the set of Pareto-optimal solutions for multi-objective supply chain network design problem. Fleischmann, Ferber and Henrich (2006) develops a strategic-planning model for BMW to optimize the allocation of products to global production sites over a finite planning horizon. We refer the reader to Shapiro (2007) and Simchi-Levi, Kaminsky and Simchi-Levi (2009) for a thorough review of supply chain modeling and strategies.

The material supply chain design literature provides important modeling and solution methodologies that can be useful in designing an energy supply chain. However, an energy supply chain is structurally different from a material supply chain section (*section 1.2*) and thus demands new models, performance metrics and insights. For instance, the unique feature of yield losses in power transmission gives rise to a new trade-off in energy supply chains (*section 1.2*) that connects the decisions of reserve selection, power plant locations, and rail/power line linkages. The limited reserves mandate the consideration of mine switching over time and thus shape the dynamic nature of the model. The interaction between energy consumption and economy (GDP) not only endogenizes the budget (in contract to exogenous budget often assumed in the material supply chain literature), but also introduces a dynamic feedback loop that could play a significant role in system design and configuration. Finally, energy infrastructure development must account for environmental issues in addition to conventional cost factors.

The energy sector is gaining increasing attention from operations and supply chain management researchers. We refer the reader to Hu, Kapuscinski and Lovejoy (2011) for a study of auctions in the wholesale electricity markets, Secomandi and Seppt (2013) for a monograph that provides an integrated finance and operations perspective, and Fang, Misra, Xue, Yang (2012) for a survey on smart grid - how to improve efficiency and reliability of existing energy systems. To the best of our knowledge, energy supply chain design is not studied in the operations and supply chain management literature. In this paper, we extend the literature of supply chain management from physical goods to the energy and energy resources by developing a new class of location models to capture the unique features of the energy supply chain.

3.1.2 Energy Economics and Policy

The energy policy and economics literature studies the specific features of an energy supply chain. Such studies are either empirical or analytical but often focus on individual parts of an energy supply chain rather than the supply chain as a whole.

The causal relationship between energy consumption and economy (GDP) is one of most widely studied relationships in this literature. In the economic theory, energy is considered as an input factor in the production function along with capital and labor. Therefore energy consumption is regarded as one of the key drivers of economic growth. Solow (1956) is among the first to develop a theory based on Cobb-Douglas equations to study the influence of energy on the economy. Ever since, the relationship is empirically estimated and justified by many authors using various data sets. For instance, Oh and Lee (2004) performs a multivariate analysis on Korea over the period 1970-1999, which suggests a long-run bidirectional causal relationship between energy and GDP, and a short-run unidirectional causality running from energy to GDP. Narayan, Narayan and Popp (2010) conducts a multi-country analysis and confirms that energy consumption has a positive impact on real GDP in countries like Japan, Malaysia, Pakistan, Sri Lanka, Thailand, and Vietnam. Menegaki (2014) performs a meta-analysis of 51 studies published in the last two decades, and shows that on average, 1% increase in capital increases the elasticity of GDP with respect to energy consumption by 0.85%. Multiple studies focus on Pakistan and justify the causality from electricity consumption to economic growth or industrial output (Shahbaz and Lean 2012, Shahbaz, Zeshan and Afza 2012, Tang and Shahbaz 2013).

Analytical studies and mathematical modeling in the energy economics and policy literature focus on three important parts of an energy supply chain: (i) power plant operations and locations, (ii) power plant fuel transportation, and (iii) electricity transmission.

The literature studies location issues of power plants related to solar, nuclear, wind and thermal sources. Dutton, Hinman and Millhamet (1974) studies the optimal location of nuclear-power plants with respect to construction, operating, and transmission costs. The mathematical model was solved by the simplex method in conjunction with a branch and bound procedure. Barda, Dupuis and Lencioniet (1990) uses the industrial feasibility standard approach to evaluate the best possible location of power plants. The paper considers gas transportation by pipelines that differs from coal energy economics. Rietveld and Ouwersloot (1992) proposes stochastic dominance concepts to rank alternatives among possible locations for nuclear power plants. An integrated hierarchical approach is presented by Azadeh, Ghaderi and Maghsoudi (2008) to select the best-possible location for solar power plants with the lowest costs. This literature also studies power plant operations. For instance, Liu, Huang, Cai, Cheng, Niu, and An (2009) develops a mathematical programming based optimization model for coal and power management to improve the efficiency of a coal-based power plant. Godoy, Benz and Scenna (2012) provides a non-linear programming model to optimize the long-term operations of natural gas combined-cycle power plants.

The literature also studies the fuel transportation and power transmission issues. For instance, Mathur, Chand and Tezuka (2003) studies the optimal utilization and transportation of thermal coal and develops a framework of the general transportation problem based on a linear programming model. Bowen, Canchi, Lalit, Preckel, Sparrow and Irwin (2010) presents a mathematical programming based multi-period planning model to optimize and expand power transmission system in India with growing demand for electricity. Paulus and Truby (2011) studies the impact of energy transport decisions on the global steam coal market by a spatial equilibrium model. Rosnes and Vennemo (2012) builds an optimization model to estimate the cost of providing electricity to Sub-Saharan Africa over a 10-year period. These papers consider existing power plants and thus power plant location is not an issue.

All aforementioned analytical papers study individual parts of an energy supply chain rather than the energy supply chain as a whole. Recently, the potential of such an integrated approach is acknowledged by Halldorsson and Svanberg (2012), which conceptually explains how supply chain management may have a great potential in applications to the production, accessibility and use of energy, from the point of origin to the point of consumption. The paper also points out that "supply chain research has only to a limited extent explored the nature of energy and energy resources."

Our work expands the energy economic and policy literature to study an integrated energy supply chain from coal mining to power consumption based on supply chain management principles and mathematical programming models. For the first time, we incorporate the new trade-off between inbound and outbound costs as well as the dynamic nature of energy supply systems, such as, limited reserves and energy-GDP interaction, in deciding reserve selection and power plant locations. Applying the model to the real-life situation of Pakistan, we present novel solutions that significantly outperform the government's plan in resolving the energy crises and shed new insights on energy supply chain design.

3.2 Static Analysis

For a better understanding of energy supply chain, we conduct static analysis to examine the interplay of key components of this energy chain. These components are: (1) location of demand zones, (2) major electricity demand requirements across the country, (3) location of coal reserves in relation to demand zones, and (4) analysis of transmission cost vs. transportation cost. The heuristics developed will help us to understand the significance of location of dispersed demand zones and coal mines.

3.2.1 Assumptions

In this section, we define assumptions for static models of coal-fired energy supply chain. Location of coal mines, demand zones and contribution of major provinces towards GDP is shown in *Figure 3.1*.

Figure 3.1: Pakistan coal reserves, demand zones and major GDP provinces.
Soruce: Modified from "Nations Online Project".

We considered following assumptions for static coal-fired energy supply chain:

1. *We assume two coal mines Thar and Salt Range for these static settings. These mines are assumed to have unlimited reserves so that demand in planning horizons*

of 25 or 50 years can be met.

2. *We assume two major demand zones; Punjab (industrial hub) and Sindh (commercial hub). For Punjab demand zone, Sahiwal city is considered as the center of this demand zone. For Sindh, Karachi city is considered as the center of demand zone.*

3. *We assume constant energy demand gaps over 25 and 50 years time horizon.*

4. *We assume that unlimited funds are available under all settings to develop whole energy supply chain without any budget restrictions.*

5. *We assume that all the power plants are built at one location unless mentioned otherwise. For both demand zones (Punjab and Sindh) few potential locations between coal mines and demand zones are identified where we can also build power plants.*

6. *We do not consider any operating costs for power plants, coal mines, railway network etc.*

7. *We do not consider construction times for power plants, transmission lines, railway network and mine infrastructure development.*

8. *All power plants use the latest IGCC (integrated gasification combined cycle) technology with a capacity of 300 MWh. All power plants operate at full capacity.*

9. *The railway linkages between a mine and a power plant location is dedicated and require dedicated coal freight trains.*

10. *Building a power plant at a mine requires new transmission; building it at a demand zone requires upgrading of existing transmission network.*

11. *The yield loss of transmission lines is 8% every 100 miles.*

3.3 Mathematical Models

3.3.1 Model-1: Single source, single demand zone

In *Model-1*, one demand zone Punjab is considered. The energy requirement for this demand zone is assumed as 20,000 MWh. Seven possible potential locations are identified where we can build power plants to satisfy Punjab demand (*Figure 3.2*). Coal transportation is assumed through railway network.

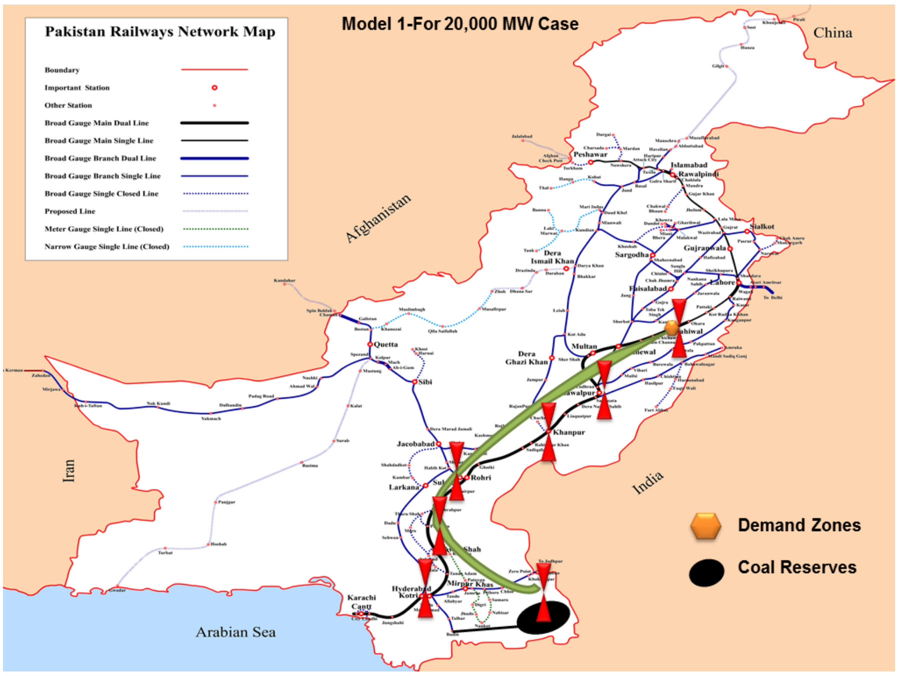
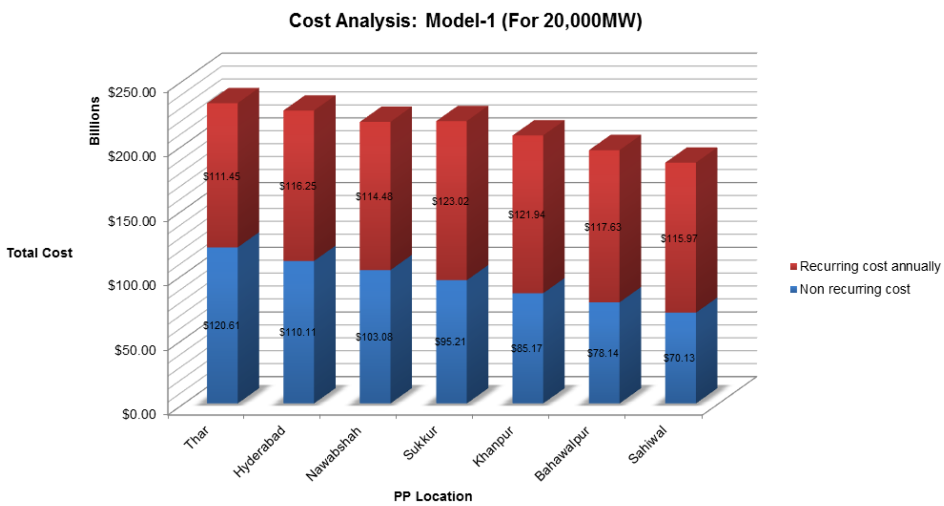


Figure 3.2: Map Model-1

When power plants are built at mine, transmission line infrastructure is required to transmit electricity from mine to demand zone. However, for locations other than the mine, railway network is required to transport coal from mine to PPs location and transmission network is required to transmit electricity from PPs to grid station.

Furthermore, whenever the PPs are built at coal mine we do not need coal transportation infrastructure but we need to consider transmission line and grid station cost. The yield loss associated with the transmission line is 8% per 100 mile. It means that for every 100 miles of transmission line used there is an associated yield loss factor. Due to yield loss, extra power needs to be generated to compensate the transmission loss. More yield loss will result an increase in fixed cost that means increase in capital cost of additional power plants.



PP Location	*Thar*	*Hyderabad*	*Nawabshah*	*Sukkur*	*Khanpur*	*Bahawalpur*	*Sahiwal*
Total Discounted Cost	*$232.05*	*$226.36*	*$217.56*	*$218.22*	*$207.11*	*$195.77*	***$186.10***

Figure 3.3: Cost Analysis: Model-1

Cost analysis for the optimal location of PPs for above described setting is shown in *Figure 3.3*. The minimum cost ($186 billion) incur when PPs are built at the demand zone, Sahiwal in this case. It means that farther the demand zone from the source the yield loss factor becomes significant as compared to the cost of coal of transportation.

The importance of trade-off between coal transportation cost and transmission yield loss discussed in section (§1.2) is identified in *Model-1*. We can conjecture from *Model-1* that in case we have only one mine and one demand zone, it is optimal to locate all power plants at demand zone.

The next scenario discussed in *Model-2* raised the question that how the optimal location of PP will be adjusted if there are two demand zones, one near and other away from the mine?

3.3.2 Model-2: Single source, two demand zones

In *Model-2*, we considered Punjab (50,000 MWh) and Sindh (20,000 MWh) demand zones. Eight potential location for PPs are considered from source to the demand zones.

Different locations of power plant are shown in *Figure 3.4*. When PPs are built at source, Thar mines, only transmission network is required. However, for locations other than the source, railway network will be used for transportation of coal from mine to the PPs in combination of transmission network for electricity transmission.

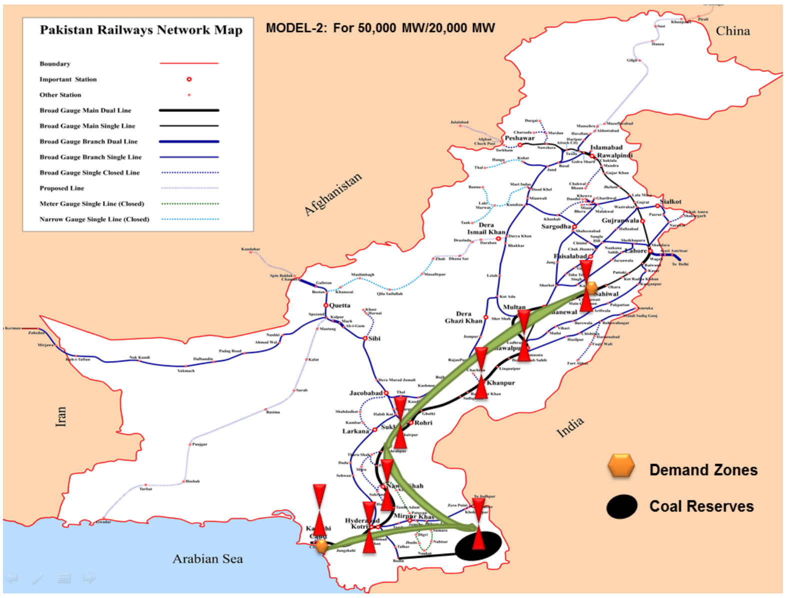
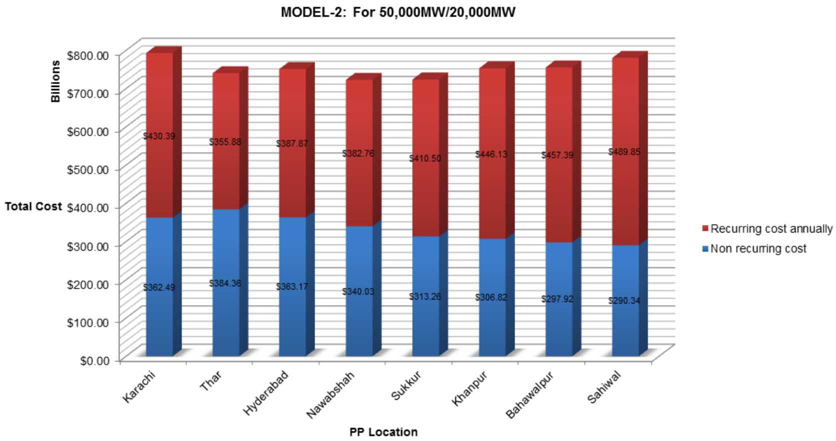


Figure 3.4: Map Model-2

In comparison to *Model-1*, yield loss associated with the transmission line will be more due to multiple (two) demand zones. The presence of an additional demand zone will incur extra cost in terms of yield loss and correspondingly more number of power plants will be required to fulfill the energy requirements of both demand zones simultaneously.

As shown in *Figure 3.5*, Nawabshah, a location between two demand zones and Thar mines, incur minimum cost ($722 billion) under these settings. In comparison to *Model-1*, the optimal location of PPs is changed from the demand zone to a location between source and demand zone.

Model-2 explains the significance of dispersed demand zones and its impact on energy supply chain. The solution is robust and opens up new dimensions to explore with different settings of energy supply chain.



PP Location	*Karachi*	*Thar*	*Hyderabad*	*Nawabshah*	*Sukkur*	*Khanpur*	*Bahawalpur*	*Sahiwal*
Total Discounted Cost	*$792.87*	*$740.23*	*$751.04*	***$722.79***	*$723.76*	*$752.94*	*$755.31*	*$780.18*

Figure 3.5: Cost Analysis: Model-2

3.3.3 Model-3: Single source, two demand zones, two PP locations

In *Model-3* we relaxed the constraint of building all power plants in one location and examined what will happen if we use a separate power plant location for each of the two demand zones (Punjab and Sindh)?

Seven possible potential locations for power plants are considered for Punjab (50,000 MWh) demand zone. For Karachi (20,000 MWh), three possible potential locations for power plant locations are identified. Other settings of coal transportation, railway network and transmission network remain the same.

Decomposition strategy for Punjab demand zone is shown in *Figure 3.6*. In this case, Thar (coal mines) is assumed to supply coal for PP locations allocated for Punjab demand.

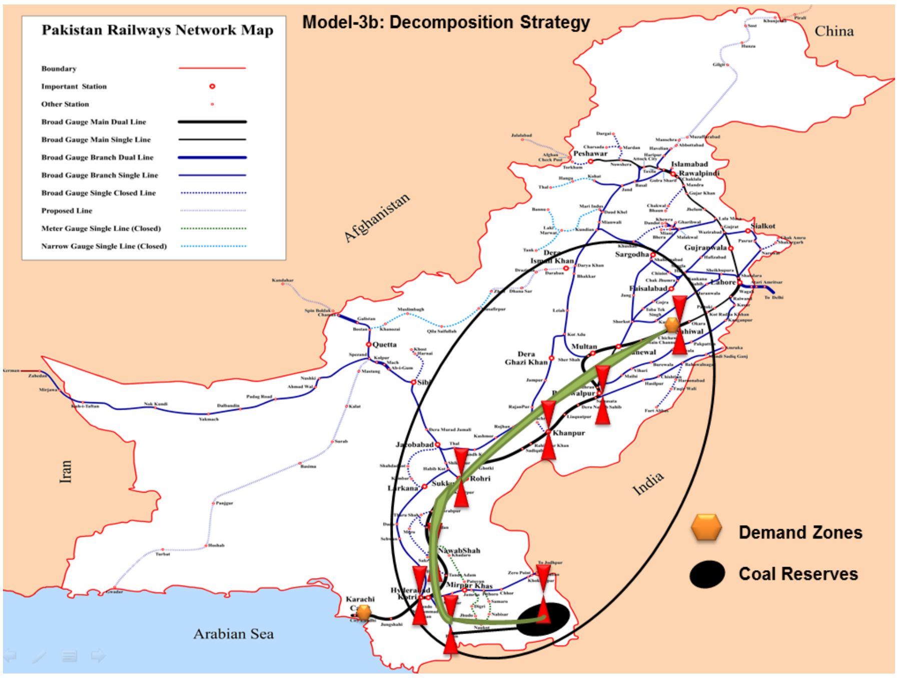


Figure 3.6: Map Model-3a

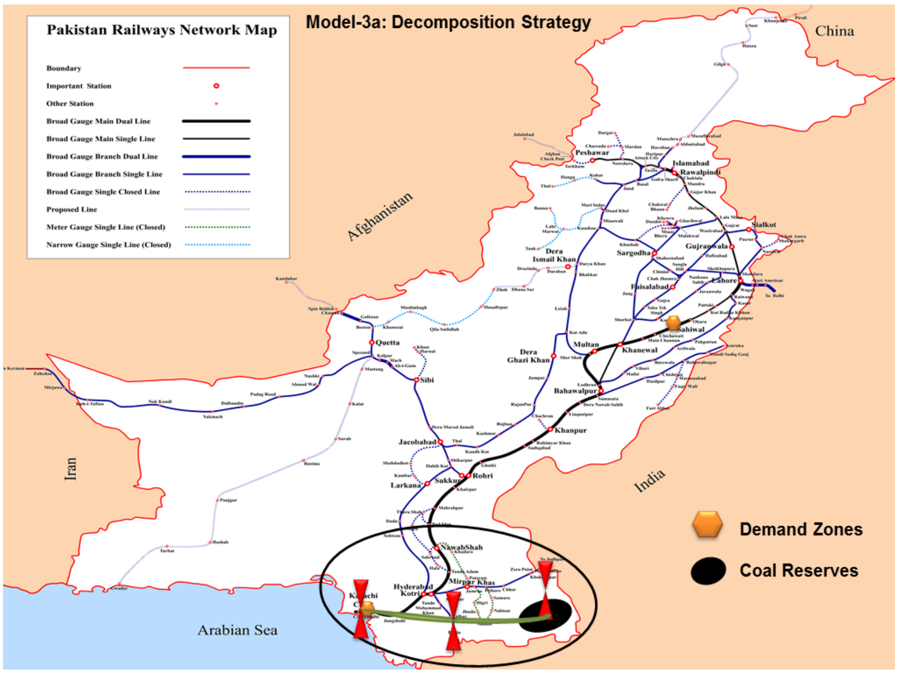
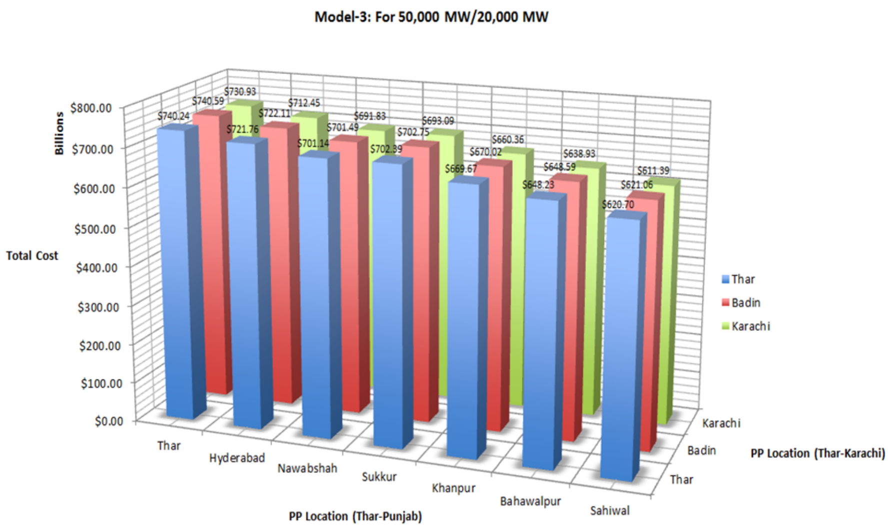


Figure 3.7: Map Model-3b

Similarly, the locations of PPs to fulfill Sindh demand are shown in *Figure 3.7.* Both the models are analyzed separately and economics of coal transportation and yield loss is calculated from the Thar (coal mines) for each demand zone.

Same settings for transmission network and railway network are used as in previous models. Minimum cost ($611 billion) is incurred when PPs are located at respective demand zones (Sahiwal and Karachi). It is important to note that result remains same for both demand zones irrespective of the distance of demand zones from coal mines as shown in *Figure 3.8.* This strategy costs less as compared to the strategy of building PPs at one location and satisfying the demand of two demand zones as in *Model-2*.



50,000 MW / 20,000 MW	*PP Locations*	*Thar*	*Hyderabad*	*Nawabshah*	*Sukkur*	*Khanpur*	*Bahawalpur*	*Sahiwal*
1	***Thar***	*$740.23*	*$721.75*	*$701.13*	*$702.39*	*$669.66*	*$648.23*	*$620.70*
2	***Badin***	*$740.59*	*$722.11*	*$701.49*	*$702.74*	*$670.02*	*$648.58*	*$621.05*
3	***Karachi***	*$730.93*	*$712.44*	*$691.82*	*$693.08*	*$660.36*	*$638.92*	***$611.39***

Figure 3.8: Cost Analysis Model-3

The results obtained under this setting are quite intuitive and explains that it is important to have the flexibility of building PPs at multiple locations. The savings can be substantial for multiple scattered demand zones in comparison to *Model-2*. Even when, Thar coal mine is close to Sindh (minor demand zone) but far away from Punjab (major demand zone) the minimum cost is incurred when the PPs are built at respective demand zones.

These results lead to another setting that needs to be evaluated to gain better understanding of structural properties of current energy supply chain. In new settings (*Model-4*) we will find the optimal location of PPs in presence of another mine (Salt Range) with unlimited coal reserves which are close to major demand zone Punjab.

3.3.4 Model-4: Two sources (unlimited), two demand zones

This model involves setting of two coal mines, Thar and Salt Range, assuming both have unlimited coal reserves. The settings for sub-models are described below: ‘

1. *Model 4a : Use Thar (coal mines) for both Punjab and Sindh demand zones.*
2. *Model 4b: Use Salt Range (coal mines) for both Punjab and Sindh demand zones.*
3. *Model 4c: Use Salt Range (coal mines) for Punjab (large) demand zone.*
4. *Model 4d: Use Thar (coal mines) for Sindh (small) demand zone.*

A detailed description of these settings are discussed as follows:

- *Model-4a: Use Thar mines for both Punjab and Sindh demand zones*: This setting is same as discussed in section (§3.3.2). For the sake of continuity results are presented here in context of the problem.

In *Model-4a*, we considered Punjab (50,000 MWh) and Sindh (20,000 MWh) demand zones. Eight potential location for PPs are considered from source to the demand zones.

Different locations of power plant are shown in *Figure 3.9*. When PPs are built at source, Thar mines, only transmission network is required. However, for locations other than the source, railway network will be used for transportation of coal from mine to the PPs in combination of transmission network for electricity transmission.

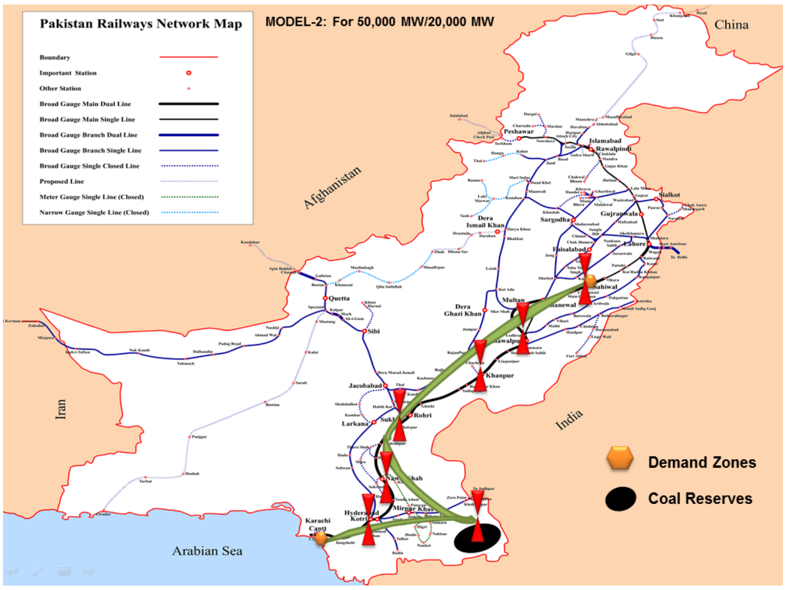
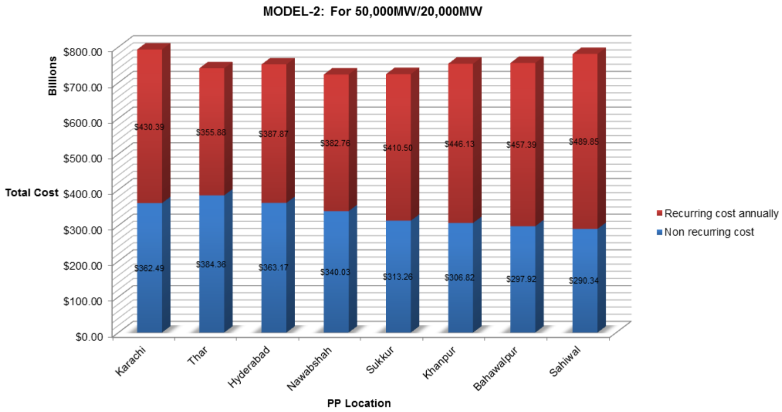


Figure 3.9: Map Model-4a

As shown in *Figure 3.10*, Nawabshah, a location between two demand zones and Thar mines, incur minimum cost ($722 billion) under these settings. In comparison to *Model-1*, the optimal location of PPs is changed from the demand zone to a location between source and demand zone.



PP Location	*Karachi*	*Thar*	*Hyderabad*	*Nawabshah*	*Sukkur*	*Khanpur*	*Bahawalpur*	*Sahiwal*
Total Discounted Cost	*$792.87*	*$740.23*	*$751.04*	***$722.79***	*$723.76*	*$752.94*	*$755.31*	*$780.18*

Figure 3.10: Cost Analysis: Model-4a

Model-4a explains the significance of dispersed demand zones and its impact on energy supply chain.

- *Model 4b: Use Salt Range mines for both Punjab and Sindh demand zones.* Salt Range mines are used for Punjab and Sindh demand zones. The different locations of the power plants are shown in *Figure 3.11*. When power plants are built at the mine or away from the source, transmission network and railway network settings are same as discussed in previous models.

  Minimum cost ($738 billion) of building PPs with two demand zones (Punjab and Sindh) and Salt Range (coal mines), will incur when all power plants are located at major demand zone Sahiwal which is center of Punjab demand zone (*Figure 3.12*).

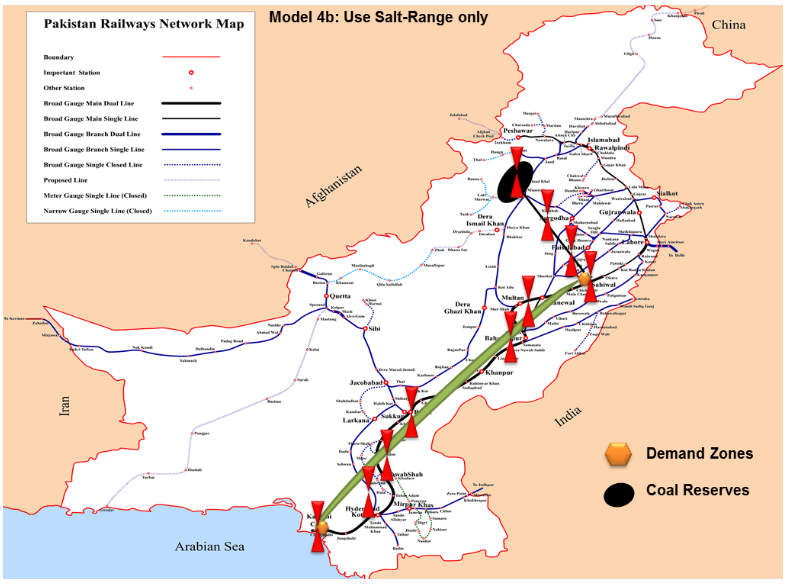
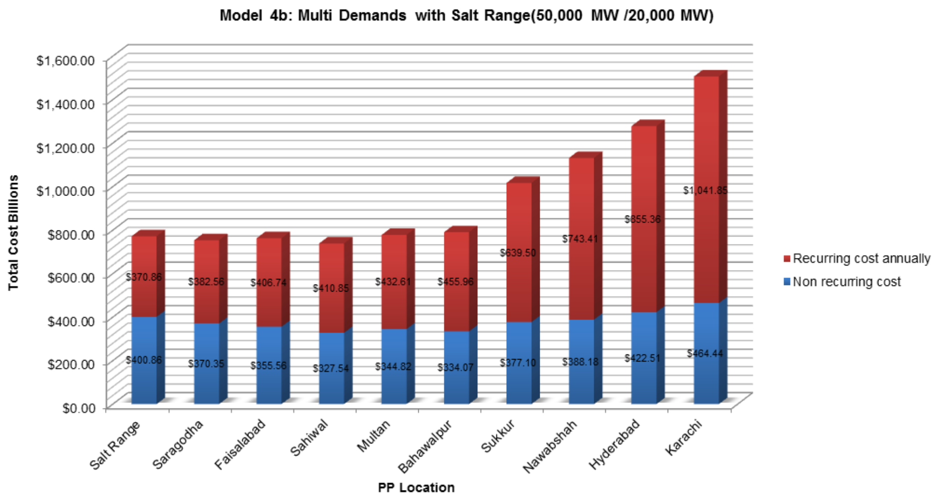


Figure 3.11: Map Model-4b



PP Location	*Salt Range*	*Saragodha*	*Faisalabad*	*Sahiwal*	*Multan*	*Bahawalpur*	*Sukkur*	*Nawabshah*	*Hyderabad*	*Karachi*
Total Discounted Cost	*$771.72*	*$752.9*	*$762.30*	***$738.38***	*$777.42*	*$790.03*	*$1016.59*	*$1131.59*	*$1277.86*	*$1506.29*

Figure 3.12: Cost Analysis: Model-4b

The solution is quite interesting; as with the change in coal mine from Thar to Salt Range, the optimal location to build PPs turns out to be Sahiwal (center of Punjab demand zone) which is close to Salt Range.

- *Model-4c: Use Salt Range mines for Punjab demand zone only.* In this setting, we only considered Punjab demand zone. Salt Range mines are assumed to supply coal for this demand zone.

The different locations of PPs are shown on the map (*Figure 3.13*). When power plants are built at coal mine or away from the source, the requirements for transmission and railway network are same as in previous models.

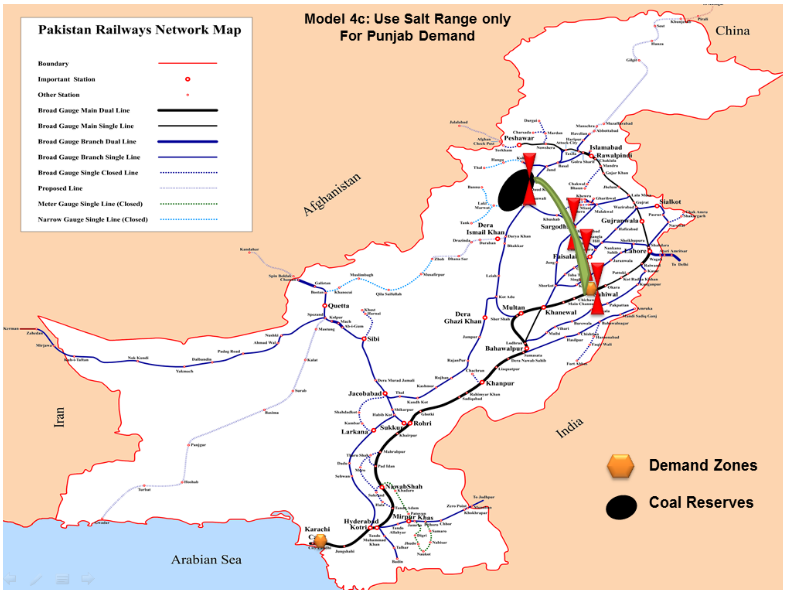
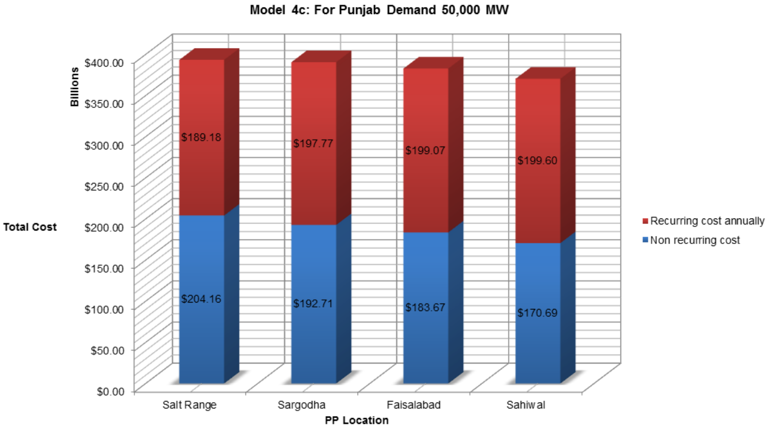


Figure 3.13: Map Model-4c

From *Figure 3.14*, the minimum cost will incur when all the PPs are located at the demand zone, Sahiwal (center of Punjab demand). Consistent with *Model-4b*, the optimal location for PPs remains with the demand zone, even with one demand zone (Punjab) and one mine (Salt Range).



PP Location	Salt Range	Sargodha	Faisalabad	Sahiwal
Total Discounted Cost	$393.33	$390.47	$382.73	$370.29

Figure 3.14: Cost Analysis: Model-4c

- *Model-4d: Use Thar mines for Sindh demand zone only.* Different locations of PPs are shown in *Figure 3.15*. Railway network and transmission network settings are same as as discussed in previous models.

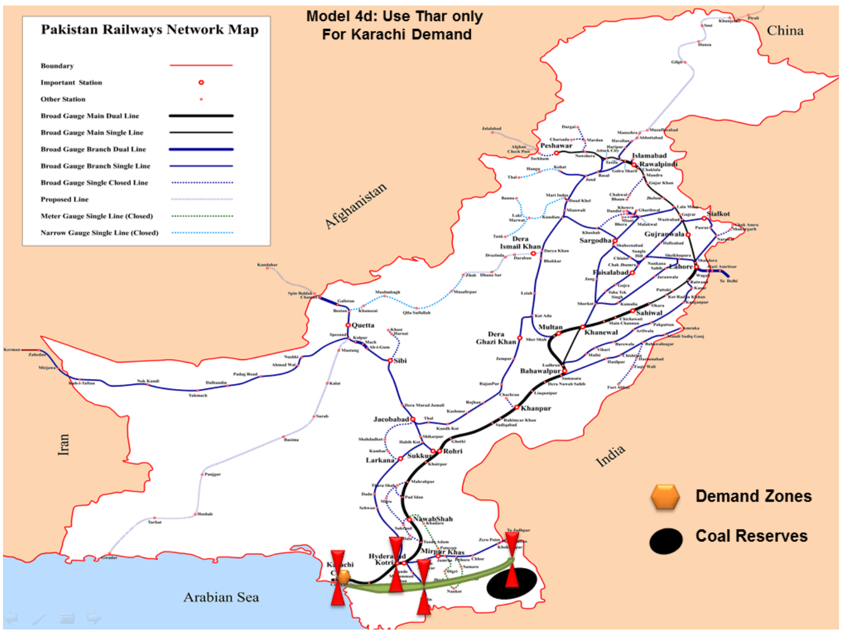
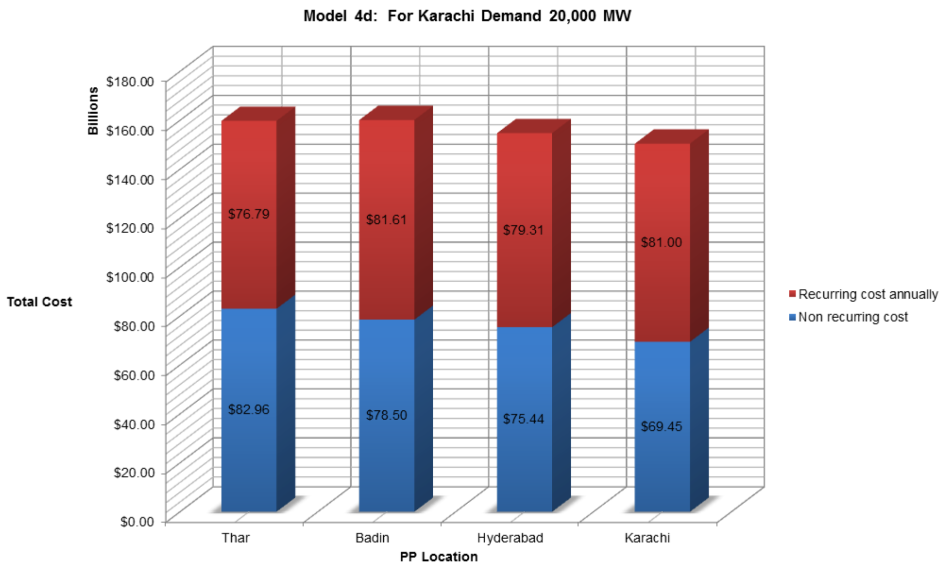


Figure 3.15: Map Model-4d

As shown in *Figure 3.16*, the minimum cost ($150 billion) will incur when all the PPs are located at center of Sindh demand zone (Karachi). The results obtained for this particular setting of mine (Thar) and the demand zone (Sindh) the optimal location for PPs is consistent with *Model-4c*. Total cost for the whole demand (from *Model-4c* and *Model-4d*) will be $\$370 + \$150 = \$520$ billion.



PP Location	*Thar*	*Badin*	*Hyderabad*	*Karachi*
Total Discounted Cost	*159.75*	*$160.11*	*$154.75*	***$150.45***

Figure 3.16: Cost Analysis: Model-4d

3.4 Summary

In this chapter we studied different combinations of mines and power plant locations from *Model-1* to *Model-4* under certain assumptions to understand structural properties of energy supply chain.

In *Model-1* (single mine, Thar, and single demand zone, Punjab) the optimal location of power plants is identified as Sahiwal (center of Punjab demand zone) at a cost of

$**186** billion. Analysis of results provide some insights about the cost variation from mine to the demand zone. *Figure 3.17* explains the trade-off identified in *Model-1*. As we move away from the mine, the cost of railway network along with coal transportation cost increases. On the other hand, when we only use transmission network, transmission yield loss results in increased capital cost that is required to build more power plants. From cost analysis, we infer that it is important to consider the trade-off (*Figure 3.17*) between coal transportation cost and transmission yield loss.

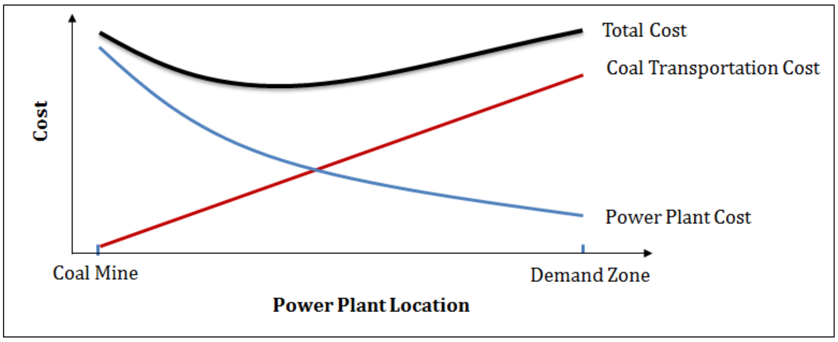


Figure 3.17: Trade-Off Analysis

In *Model-2*, Sindh was introduced as second demand zone. The demand or energy requirement for Punjab and Sindh were assumed as 50,000 MWh and 20,000 MWh respectively. With same settings of mine, railway network and transmission network the optimal location to build power plants with two dispersed demand zones (Punjab and Sindh) and single source (Thar) turned out between mine and demand zones at an optimal cost of $**722** billion. This clearly showed the importance of dispersed demand zones. The output of this setting of supply chain is totally different from *Model-1*, as the optimal location is changed from demand zone to a new location between mine and demand zones. The result obtained in *Model-2* signifies the importance of dispersed demand zone on energy supply chain.

In *Model-3*, we adopted a separation strategy with flexibility of building PPs at two locations to satisfy the demand of two demand zone, Punjab and Sindh. Same mine (Thar), energy requirements, railway network and transmission network settings are considered as in *Model-2*. The problem was treated as two separate sub problems for each demand zone by using the same coal mine (Thar). Due to the flexibility of two locations for PPs, building the PPs at the demand zones identified as optimal locations for both demand zones. Optimal cost of building power plants at respective demand zones was calculated around \$611 billion with cost savings (as compared to *Model-2*) around \$722 − \$611 = \$**111** billion. For separation strategy, building power plants at respective demand zones (Punjab and Sindh) was identified as an optimal approach. The results confirmed that for multiple scattered demand zones savings can be substantial as compared to concentration of PPs at one location.

In *Model-4*, we considered two coal mines (Thar and Salt Range) and two demand zones (Punjab and Sindh). The combination of these mines and demand zones are evaluated in detail.

In *Model-4a*, we used Thar coal mine and two demand zones (Punjab and Sindh). The results are same as discussed in *Model-2*. The optimal location found resulted in Nawabshah, which is located between mine and demand zones. The optimal cost for this setting was \$**722** billion.

In *Model-4b*, we used Salt Range coal mine and two demand zones (Punjab and Sindh). The optimal location turned out to be at the center of Punjab demand zone, Sahiwal.

The optimal cost of this supply chain was around $**738**. The results indicate the impact of change in location of coal mine with respect to demand zones.

In *Model-4c*, only Salt Range coal mine in combination of Punjab demand zone is considered. Optimal location (cost = $**370** billion) for Punjab demand using Salt Range only was found at the Sahiwal (center of Punjab demand zone). In *Model-4d*, only Thar coal mine in combination of Sindh demand zone is considered. Optimal location (cost = $**150** billion) for Sindh demand using Thar only was found at the Karachi (center of Sindh demand zone). Total cost for the whole demand was calculated as; $\$370 + \$150 =$ $**520** billion with savings (as compared to *Model-3*) around $\$611 - \$520 =$ $**91** billion. From cost analysis we concluded that having a nearby mine to serve each demand zone is advantageous. Moreover, Salt Range proved valuable because it is closer to the major demand zone.

Recall in section (§1.1), the government plan outlines the use of Thar coal mines only, to develop energy supply chain. Government plan is close to the settings discussed in *Model-2* with a total cost of approximately $732 billion. However from these heuristics it is clear that the use of both coal mines, Salt Range and Thar, is more economical at $**520** billion.

The analysis of these models provide a framework to explore this problem in more detail. In reality, the assumptions followed in above described settings are more strict and problem becomes more complicated considering the limited availability of funds, annual growth of energy demand, identification of potential locations for power plants, number of power plants at each potential location, setup cost and time for power plants, railway network, transmission network, and coal mine infrastructure. The nature and complexity of this type of dynamic energy supply chain problem requires an optimization based mathematical programming model discussed in *Chapter-4*.

Chapter 4

Dynamic Energy Supply Chain

In this chapter, we apply supply chain management principles and mathematical programming to the energy sector and present a new class of mathematical models for designing coal-fired energy supply chains. For the first time, the model captures the trade-off between inbound and outbound costs in an integrated energy supply system from coal mining to power generation and to power consumption. Also for the first time, the model incorporates the dynamic interaction between energy consumption and economy, and consider limited reserves and the need to switch after they run out. The resulting mathematical model is a multi-period mix integer program (MIP) aiming at minimizing energy gaps among all demand zones by building up an energy supply chain gradually under limited budgets. Decisions are on reserve selection, power plant location, coal transportation and power transmission linkages. Performance metrics are cost per MWh consumed, energy gap, GDP growth, and coal burnt per MWh consumed (to measure environmental impact).

The mathematical model produces solutions drastically different from the government's plan. In all cases (under different budgets, planning horizons, demand growth rates), the optimal solutions utilize a tiered strategy which first explores the smallest nearby reserve in Punjab (in the north), then the medium reserve in Sindh (in the south), and finally the largest reserve in Thar (if the planning horizon is sufficiently long). Power plants are spread out in both north and south near demand zones and are supplied locally from the smallest and medium size reserves respectively. After the smallest reserve in the north runs out, all power plants will be supplied by the medium and large reserves in the south. The optimal solutions outperform government's plan significantly by reducing the energy gaps much faster, boosting the economy much stronger with much less greenhouse gas emissions per MWh consumed.

The rest of this chapter is organized as follows; In sections *4.1-4.2*, we present assumptions and justifications, the conceptual model, and the mathematical model in full detail. In section *4.3*, we demonstrate the effectiveness of the model and its solutions through the real-life example of Pakistan in comparison to the government's plan. Section *4.4* concludes this chapter.

4.1 Preliminaries

In this section, we make assumptions for a coal-fired energy supply chain and justify them by practices and standards in the energy sector. We then present a conceptual framework to outline the structure of the mathematical model.

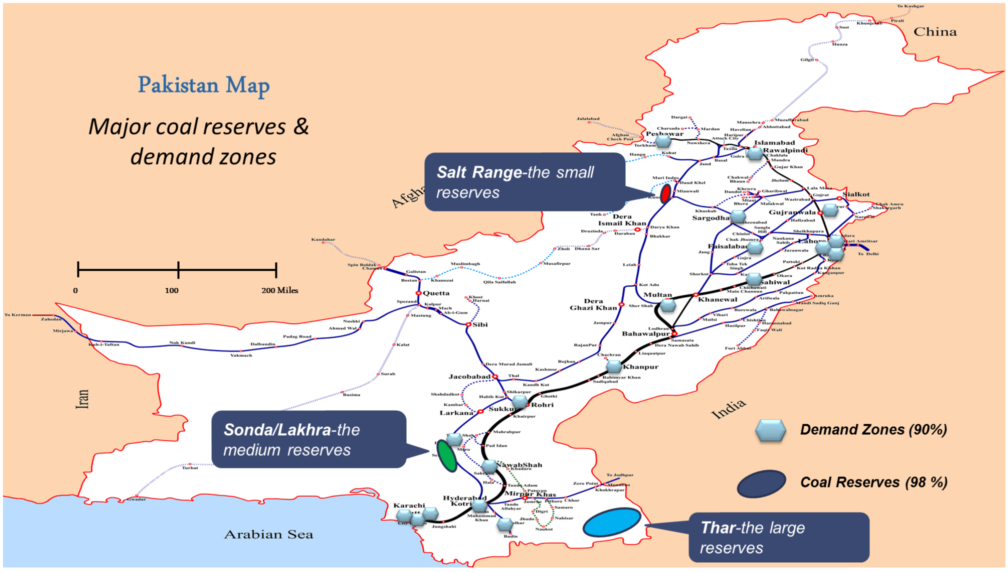


Figure 4.1: Pakistan map with major coal reserves and demand zones.

Figure 4.1 shows map of Pakistan coal reserves and major demand zones. A thorough case study of Pakistan's energy crises by Rafique and Zhao (2011) provides the following observations.

Observation 1. *Observations on the coal-fired energy supply chain of Pakistan:*

1. *Three largest coal reserves (Figure 4.1): Thar, Sonda/Lakhra and Salt Range, account for 98% of Pakistan's total coal reserves,* $J = 3$. *The amount of reserves that are of sufficient quality for power generation is listed in Table 4.1. As we can see, Thar and Sonda/Lakhra reserves have ample supply to meet demand in a planning horizons of 25 or 50 years but Salt Range does not.*

2. *There are 19 demand zones that account for 90% of the country's total energy consumption (4.1),* $N = 19$. *14 of them are major energy-consumption cities and 5 of them are smaller cities but ideal locations for power plants. Demand for energy*

is estimated to grow at a rate of 5-7% annually (1.2).

3. *The potential locations for power plants include all reserves and demand zones, thus there are 22 locations ($K = 22$).*

4. *There is no limit on the number of power plants that can be built at the three coal reserves, that is, $UB_j = +\infty$ for $j \in \mathcal{K}_R$ where $\mathcal{K}_R$ is the set of power plant locations at coal reserves. For demand zones, at most ten power plants ($UB_j = 10$) can be built in each of the five smaller cities $j \in \mathcal{K}_S$; at most five power plants ($UB_j = 5$) can be built in the other bigger cities $j \in \mathcal{K}_B$.*

We consider a planning horizon of either 25 years or 50 years ($T = 25$ or 50).

Name	**Province**	**Reserves (Million Tons)** $CR_j/10^6$	**Years of 10,000 MWh generated**
Salt Range	*Punjab*	213	9
Sonda and Lakhra	*Sindh*	8,440	350
Thar	*Sindh*	175,000	7,251

Table 4.1: Pakistan Coal Reserves. Source: Rafique and Zhao (2011).

Table 4.2 summarizes the model parameters for Pakistan. For capital projects that last multiple years, we assume that the total investment is evenly distributed over the duration.

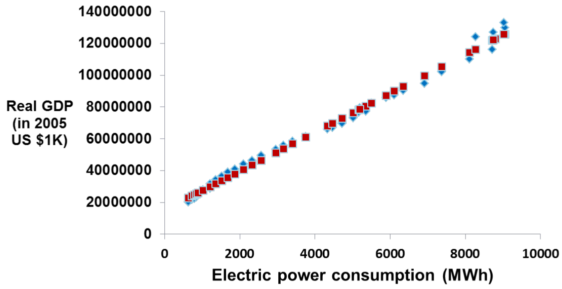
Note that the mine setup costs, I_j^{CM}, include water supply related costs. The matrices of D_{jk} and D_{kn} are determined by the geology and transportation network of Pakistan. $RT_{jk} = 2D_{jk}/0.5 + LT + UT$ where 0.5 refers to the average train speed of 50 miles/hour, and LT (UT) refers to loading (unloading, respectively) time. $F_{jk} = 24/RT_{jk} * 365$ where the numbers 24 and 365 refer to 24 hours a day and 365 days a year respectively. G_{nt} depends on the demand of the starting year and the projected growth rate. The cost

Mines:		
T_1^{CM}	Setup time for *Thar* reserve	5 years
T_2^{CM}	Setup time for *Sonda/Lakhra* reserve	3 years
T_3^{CM}	Setup time for *Salt Range* reserve	3 years
I_1^{CM}	Annual investment for mine setup at *Thar*	$6,000,000/5$ in *$1,000*
I_2^{CM}	Annual investment for mine setup at *Sonda/Lakhra*	$2,000,000/3$ in *$1,000*
I_3^{CM}	Annual investment for mine setup at *Salt Range*	$500,000/3$ in *$1,000*
OC^{CM}	Unit operating cost at mines	5.33×10^{-3} per *ton* in *$1,000*
Railway / Train:		
T^{RW}	Setup time for railways	3 (5) years for upgrading (for new)
RT_{jk}	Round trip time between j and k	in *hour*
C^{TR}	Load of one train	15,000 per train, in *ton*
F_{jk}	Maximum annual frequency of a train on the railway between j and k	N/A
SC_{jk}^{RW}	Setup cost of the railway between j and k	in *$1,000*
OC^{RW}	Unit operating cost for railway coal transport	0.04×10^{-3} per *ton* per *mile*, in *$1,000*
I^{TR}	Purchasing cost of one train	50,000 per *train* in *$1,000*
Power Plant / Transmission Line:		
T^{PP}	Setup time for a standard 300 MWh power plant	3 years
I^{PP}	Annual setup cost of a standard 300 MWh power plant	1,000,000/3 in *$1,000*
OC^{PP}	Annual operating cost of a standard 300 MWh power plant	2% of the total setup cost, in *$1,000*
SC_k^{TL}	Setup cost of transmission and grid station at location k for a new power plant	in *$1,000*
Demand / Distances		
G_{nt}	Energy gap at demand zone n in year t	in MWh
D_{jk}	Distance between j and k	in 100 *mile*
D_{kn}	Distance between k and n	in 100 *mile*

Table 4.2: Parameters for Pakistan. Sources: Rafique and Zhao (2011).

matrix of railway, SC_{jk}^{RW}, is calculated by the distance matrix D_{jk} and a setup cost of \$0.73 mil./mile for upgrading (or \$13 mil./mile for new construction) (Ministry of Pakistan Railway). The setup cost of transmission and grid station for a new power plant, SC_k^{TL}, is calculated by the distance from location k to the nearest grid station and a transmission line cost of \$1.8 mil./mile for new (or \$0.6 mil./mile for upgrading) as well as a local grid station cost of \$33,000/ MWh (American Electric Power, Transmission Facts).

Our empirical study of Pakistan from 1971 to 2011 shows a strong correlation between energy consumption and real GDP (*see Figure 4.2*), which confirms the impact of energy consumption on Pakistan's economy (see Shahbaz and Lean 2012, Shahbaz, Zeshan and Afza 2012, Tang and Shahbaz 2013).



SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.9958799
R Square	0.99177677
Adjusted R Square	0.99156592
Standard Error	3229972.25
Observations	41

	Coefficients	Standard Error	t Stat	P-value
Intercept	14951524.8	891458.2	16.77199	1.99E − 19
Electric power consumption (MWh)	12254.8004	178.685	68.58327	2.81E − 42

Figure 4.2: A regression model between real GDP (in $1000) and energy consumption (in MWh) for Pakistan. Source: World Bank 2012.

The elasticity of GDP on energy consumption (slope of the regression model) is Coef = 12,254.80044. We select 2011 as the starting year ($t = 0$), and so $g_0 = 133,000,000$ (in *$1000*).

4.1.1 Assumptions and Justifications

A coal-fired energy supply chain is a network of typically three echelons: coal reserves, power plants and demand zones. The coal reserves (upper-most echelon) are mined and coal is transported by trains via railway to the power plants (middle echelon), where the coal is burnt and the generated electricity is transmitted by power lines to the demand zones (lowest echelon). *Figure 4.3* provides an overview of the network structure.

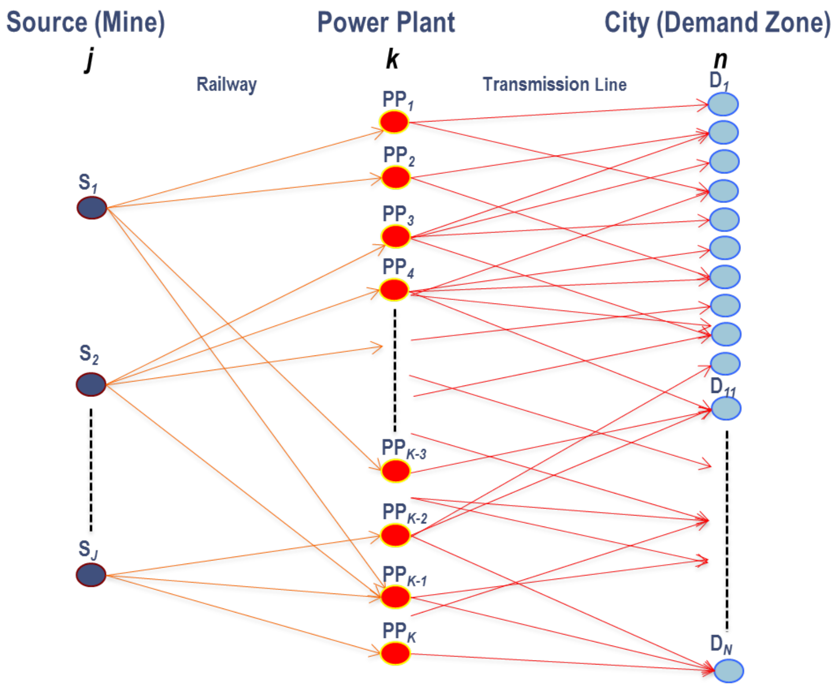


Figure 4.3: Conceptual Model: Coal-fired Energy Supply Chain.

Inspired by practice in Pakistan and standards in the energy sector, we make the following "network" assumptions.

Assumption 1. *Assumptions on the coal-fired energy supply chain:*

1. *We assume multiple coal reserves (each at a different location) for potential mining as indexed by j where $j = 1, 2, ..., J$. The amount of coal available to mine at location j is denoted as CR_j (in ton).*

2. *We assume multiple demand zones (each at a different location) as indexed by n where $n = 1, 2, ..., N$.*

3. *The potential locations for power plants include all reserves and demand zones which are indexed by k where $k = 1, 2, ..., K$. Although there is no limit on the*

number of power plants that can be built at the reserves, there are limits at demand zones (cities) due to environmental concerns.

4. *A coal mine can supply multiple power plant locations, and a power plant can be supplied by multiple mines.*

5. *A power plant can provide power to multiple demand zones, and a demand zone can receive power from multiple power plant locations.*

6. *All power plants use the latest IGCC (integrated gasification combined cycle) technology with a capacity of 300 MWh. All power plants operate at full capacity with a daily consumption of coal at 2,000 tons.*

7. *The railway linkages between a mine and a power plant location is dedicated and require dedicated coal freight trains.*

8. *Building a power plant at a mine requires new transmission; building it at a demand zone requires upgrading of existing transmission network.*

9. *The yield loss of transmission lines is* 8% *every 100 miles.*

The first two assumptions in Assumption 1 are sufficiently general to cover real-life situations in Pakistan as well as other developing countries around the world. The third assumption is based on Rafique and Zhao (2011) which provides a thorough case study of the energy crises in Pakistan. This assumption does not lose generality as we can always include potential locations for power plants as demand zones. The limitations on the number of power plants are based on pollution and environment concerns (McMullan, Williams and McCahey 2001, Kavouridisa and Koukouzasb 2008, Chen and Xu 2010). The fourth and fifth assumptions are based on the common industry practice (Rosnes and Vennemo 2012, Bowen et al. 2010). To justify the sixth assumption, we note that a power plant with the IGCC technology and 300 MWh capacity is the current standard in practice (Susta 2008). The seventh assumption can be justified by the heavy load required by power plants. The eighth assumption comes from the facts that reserves are likely unexplored in many developing countries and thus have no transmission infrastructure available, whereas in the demand zones, such infrastructure may be established and thus only an upgrade is needed to meet a higher volume. The ninth assumption is justified in (*section 1.2*).

We shall consider a planning horizon of either 25 or 50 years, and make the following "regularity" assumptions:

Assumption 2. *Regularity assumptions:*

1. *The budget is RA percent (1%, 2%, 3%, 4%, or 5%) of the real annual GDP (to eliminate the impact of inflation).*

2. *The impact of energy consumption on real GDP follows a country-specific function.*

3. *Once we start construction or updating an energy infrastructure, we must complete the job without preemption.*

4. *Power sources other than coal run as BAU (business as usual).*

To justify Assumption 2, we first note that developing countries which suffer energy deficiency can only provide limited funding for energy system development. Using Pakistan as an example, the budgetary allocation to its energy sector in the last few years ranges from 10% to 15% (Federal Budget Publications 2014-15). However, most of the budget is spent on maintenance and operations of existing infrastructures. Only a small amount is dedicated to new ventures. Thus any budget allocation of a higher than 5% of GDP to the new energy projects may be unrealistic. The impact of energy consumption on the economy (GDP) is observed and justified by the energy economics literature (see section *3.1.2* for details) and confirmed by our regression study of Pakistan in section *4.1*. We make the third assumption for convenience because of the unpredictable political circumstances in the next 25 or 50 years. We make the fourth assumption in order to focus on the energy sources of coal.

4.1.2 The Conceptual Framework

The mathematical model of an integrated energy supply chain is complex (*see section 4.2*). We shall present a conceptual framework first to outline its structure and shows intuitively how different parts are connected and interacting.

The **objective** of the mathematical model is to minimize the total discounted energy gap among all demand zones over a given planning horizon. Energy gaps are defined as the differences between projected demand and available supplies. The discounted factors represent a smaller importance for a more distant year into the future.

From the upper-most echelon to the lowest echelon of an energy supply chain, the **decision variables** are: where and when to set up a mine; the location, number and timing of power plant construction; which mine supplies which power plants; and finally which power plant supplies a demand zone and in which year.

The **constraints** can be categorized by echelons and their linkages in the energy supply chain.

1. **Mine constraints**: Reserves have limited supplies.

2. **Railway constraints**: Railway and train have capacity limits.

3. **Power plant constraints**: A limited number of power plants is allowed to built in each potential location.

4. **Network constraints**: A power plant's electricity output can't exceed the required input of energy sources (coal) and its capacity.

5. **Demand and transmission constraints**: The system can't supply more power (electricity) than needed for each demand zone.

6. **Budget constraints**: The budget is limited, and energy consumption has an impact on the economy.

While many of these constraints come from capacity limits at various parts of the supply chain, the network constraint connects coal supply with power generation and transmission, and the budget constraint provides a feedback loop from energy consumption to GDP and to the budget.

The first two categories of constraints can be divided into finer subcategories, specifying availability, capacity and budget requirement of mining, railway and coal trains. For instance, the availability constraints of a reserve indicate that it can be setup only once;

the capacity constraints honor the limit of the reserve; the budget constraints calculate the required budget. These subcategories of capacity and budget constraints also apply to power plants.

4.2 Mathematical Model

In this section, we present a mathematical model for the optimal design of coal-fired energy supply chains. We define indices in Table 4.3, which is followed by key decision variables in Table 4.4. All decision variables are non-negative.

Index	**Name**	**Set**
j	mines (reserves)	$\{1, 2, ..., J\}$
k	power plant locations $\mathcal{K}$	$\{1, 2, ..., K\}$
n	demand zones	$\{1, 2, ..., N\}$
t	time	$\{1, 2, ..., T\}$

Table 4.3: Indices

Mines			
w_{jt}	1 if mine at reserve j enters service in year t, 0 otherwise	Binary	N/A
q_{jkt}	Coal shipped from mine j to power plant location k in year t	Continuous	Unit: *ton*
Railway			
x_{jkt}	1 if the railway b/t j and k enters service in year t, 0 otherwise	Binary	N/A
nt_{jkt}	New trains purchased to ship coal b/t j and k in year t	Integer	N/A
Power Plants / Power Supplies			
y_{kt}	No. of power plants entering service at location k in year t	Integer	N/A
e_{kt}	Electricity generated at location k in year t	Continuous	Unit: *MWh*
p_{knt}	Electricity supplied from location k to demand zone n in year t	Continuous	Unit: *MWh*

Table 4.4: Decision Variables

4.2.1 Objective Function

Let ω be the yield of power transmission every 100 miles ($\omega = 92\%$), G_{nt} be the energy gap at demand zone n in year t (in MWh), and D_{kn} be the distance between power plant location k and demand zone n (in 100 miles). Let β_t be a series of time discounted factors decreasing in years, the objective function, i.e., the total discounted energy gap for all demand zones over a finite planning horizon T is,

$$\sum_{t=1}^{T}[\beta_t \cdot \sum_{n=1}^{N}\{G_{nt} - (\sum_{k=1}^{K}\omega^{D_{kn}} \cdot p_{knt})\}] \longrightarrow Min \tag{4.1}$$

The third term in the parenthesis represents the total energy consumed at demand zone n in year t.

4.2.2 Mine Constraints

The first set of constraints for mines is on their limited reserves (capacity constraints), that is, the amount of coal extracted from mine j up to time t cannot be greater than the total reserve of mine j, CR_j (in *ton*).

$$\sum_{k=1}^{K}\sum_{\tau=1}^{t} q_{jk\tau} \leq CR_j \cdot \sum_{\tau=1}^{t} w_{j\tau} \qquad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad t = 1, \ldots, T. \tag{4.2}$$

where the left-hand-side is the amount of coal extracted from mine j up to year t. Clearly, coal can only be extracted from mine j if the mine is set up (that is, $w_{j\tau} = 1$ for some $\tau \leq t$).

The second set of constraints for mines specifies their availability. Because a mine only requires one set-up, thus

$$\sum_{t=1}^{T} w_{jt} \leq 1 \qquad \text{for} \quad j = 1, \ldots, J. \tag{4.3}$$

Because each mine requires time to setup, w_{jt} must satisfy the following initial conditions: $w_{jt} = 0$, for $t = 1, 2, .., T_j^{CM}$ where T_j^{CM} is the reserve/mine specific setup time.

The last set of constraints for mines calculates their capital and operating costs. For mine j, the setup cost in year t (in \$1,000), b_{jt}^{CM1}, can be written as,

$$b_{jt}^{CM1} = I_j^{CM} \cdot \sum_{\tau=t+1}^{t+T_j^{CM}} w_{j\tau} \qquad \text{for} \quad t = 1, \ldots, T - T_j^{CM}. \tag{4.4}$$

where I_j^{CM} is the annual capital investment for setting up mining infrastructure at mine j assuming that the total investment is evenly distributed over the duration.

Because setting up the mines takes multiple years, it is logical to assume that we cannot start setting up the mining infrastructure at mine j after the $T - T_j^{CM}$th year as the mine will be ready beyond the planning horizon and thus cannot contribute to the objective function. Therefore the ending conditions for mine j are

$$b_{jt}^{CM1} = I_j^{CM} \cdot \sum_{\tau=t+1}^{T} w_{j\tau} \qquad \text{for} \quad t = T - T_j^{CM} + 1, ..., T - 1. \tag{4.5}$$

and

$$b_{jT}^{CM1} = 0. \tag{4.6}$$

Finally, the operating cost of all mines in year t, b_t^{CM2}, is given by

$$b_t^{CM2} = OC^{CM} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} q_{jkt} \qquad \text{for} \quad t = 1, \ldots, T. \tag{4.7}$$

where OC^{CM} is the unit operating cost at mines.

4.2.3 Railway Constraints

We shall only consider railway upgrading in this section. New railway construction follows the same equations but with different cost and time parameters. The first set of constraints specifies the availability of the railway. Let D_{jk} be the distance between mine j and power plant location k (in 100 *miles*) and M be a large number. Note that x_{jkt} is the indicator on the availability of the railway between j and k in year t, and nt_{jkt} is an integer variable representing new trains purchased to ship coal on this railway (Table 4.4), then

$$\sum_{t=1}^{T} x_{jkt} \leq 1 \qquad \text{where} \quad D_{jk} > 0 \quad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad k = 1, \ldots, K. \tag{4.8}$$

Constraint 4.8 ensures that the railway between mine j and power plant location k is set up only once.

$$q_{jkt} \leq CR_j \cdot \sum_{\tau=1}^{t} x_{jk\tau} \qquad \text{where} \quad D_{jk} > 0 \tag{4.9}$$

$$\text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T.$$

Constraint 4.9 indicates that coal can only be transported if the corresponding railway is set up.

$$nt_{jkt} \leq M \cdot \sum_{\tau=1}^{t} x_{jk\tau} \qquad \text{where} \quad D_{jk} > 0 \tag{4.10}$$

$$\text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T.$$

Constraint 4.10 connects trains to the availability of railway. Because a railway takes multiple years to setup, we have the following initial conditions: $x_{jkt} = 0$ for $t = 1, 2, ..., T^{RW}$ where T^{RW} is the railway setup time.

The second set of constraints is on railway capacity which depends on the frequency and capacity of trains. Let RT_{jk} be the round trip time between j and k (in *hour*), then Constraint 4.11 specifies an upper limit on the number of trains between j and k.

$$\sum_{\tau=1}^{t} nt_{jk\tau} \leq BF^{TR} \cdot RT_{jk} \tag{4.11}$$

$$\text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T.$$

where $\sum_{\tau=1}^{t} nt_{jk\tau}$ is the total number of trains purchased up to year t to operate on the railway between j and k, BF^{TR} stands for "buffer of trains", which is the maximum number of trains allowed to pass through location k in one hour. Assuming a 10-minute minimum time interval between consecutive trains, $BF^{TR} = 6$. We can choose $BF^{TR} \cdot RT_{jk}$ for the M in constraint 4.10 for the railway between mine j and power plant location k.

For the railway between j and k, we further define $C_{jk}^{TR} = C^{TR} \cdot F_{jk}$ to be the annual capacity of one train (in *ton*) where C^{TR} is the load of one train, and F_{jk} (depending on RT_{jk} and can be country specific) is the maximum frequency (number of round-trips) of a train in one year. Then

$$q_{jkt} \leq C_{jk}^{TR} \cdot \sum_{\tau=1}^{t} nt_{jk\tau} \qquad \text{where} \quad D_{jk} > 0 \tag{4.12}$$

$$\text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T.$$

Constraint 4.12 specifies the maximum railway capacity based on train capacity and frequency.

The last set of constraints for railways calculates their capital and operating costs. Let b_t^{RW1} (b_t^{RW2}) be the setup cost (operating cost, respectively) of railways in year t (in \$1,000), and b_t^{TR} be the cost of purchasing trains in year t (in \$1,000).

$$b_t^{RW1} = \sum_{j=1}^{J} \sum_{k=1}^{K} \left(\frac{SC_{jk}^{RW}}{T^{RW}} \cdot \sum_{\tau=t+1}^{t+T^{RW}} x_{jk\tau} \right) \qquad \text{for} \quad t = 1, \ldots, T - T^{RW}. \tag{4.13}$$

$$b_t^{RW2} = OC^{RW} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} (D_{jk} \cdot q_{jkt}) \qquad \text{for} \quad t = 1, \ldots, T. \tag{4.14}$$

$$b_t^{TR} = I^{TR} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} nt_{jkt} \qquad \text{for} \quad t = 1, \ldots, T. \tag{4.15}$$

where SC_{jk}^{RW} is the setup cost of railway between j and k, OC^{RW} is the unit operating cost for railway system, and I^{TR} is the purchasing cost of one train.

Because railway upgrading takes multiple years, so similar to coal mines, we have the following ending conditions.

$$b_t^{RW1} = \sum_{j=1}^{J}\sum_{k=1}^{K}(\frac{SC_{jk}^{RW}}{T^{RW}} \cdot \sum_{\tau=t+1}^{T} x_{jk\tau}) \qquad \text{for} \quad t = T - T^{RW} + 1, ..., T - 1. \tag{4.16}$$

$$b_T^{RW1} = 0. \tag{4.17}$$

4.2.4 Network Constraints

This set of constraints ensures that the power plants are adequately supplied from the mines to run at their full capacity, and all the electricity generated at each location, e_{kt}, are transmitted to demand zones.

$$e_{kt} \leq \frac{3}{20 \cdot 365} \cdot \sum_{j=1}^{J} q_{jkt} \qquad \text{for} \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{4.18}$$

where $\frac{3}{20 \cdot 365}$ is the conversion rate between coal and power as 2,000 tons of coal is needed every day for a power plant to maintain its full capacity at 300 MWh year around.

$$e_{kt} = 300 \cdot \sum_{\tau=1}^{t} y_{k\tau} \qquad \text{for} \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{4.19}$$

This constraint is based on the assumption that power plants are operated at full capacity.

$$\sum_{n=1}^{N} p_{knt} \leq e_{kt} \qquad \text{for} \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{4.20}$$

This constraint ensures that the amount of electricity transmitted is less than electricity generated at each location.

4.2.5 Power Plant and Transmission Constraints

The first set of power plant constraints is on their location dependent limitations, UB_k, which is the maximum number of power plants that can be built in location k.

$$\sum_{\tau=1}^{t} y_{k\tau} \leq UB_k \qquad \text{for} \quad k \in \mathcal{K} \quad \text{and} \quad t = 1, \ldots, T. \tag{4.21}$$

The initial condition for y_{kt} is $y_{kt} = 0$ for $t = 1, 2, ..., T^{PP}$ where T^{PP} is the setup time for a power plant.

The second set of constraints for power plants calculates their capital and operating costs. Let I^{PP} be the annual setup cost of a power plant, OC^{PP} be the annual operating cost per MWh generated (for a standard 300 MWh power plant), and SC_k^{TL} be the location-dependent setup/upgrading cost for transmission line and grid station. Then the cost of building power plants in year t, b_t^{PP1}, and the cost for building associated grid stations and power plant operations, b_t^{PP2}, are

$$b_t^{PP1} = I^{PP} \cdot \sum_{k=1}^{K} \sum_{\tau=t+1}^{t+T^{PP}} y_{k\tau} \qquad \text{for} \quad t = 1, \ldots, T - T^{PP}. \tag{4.22}$$

$$b_t^{PP2} = \sum_{k=1}^{K} \{(SC_k^{TL} \cdot y_{kt}) + (OC^{PP} \cdot e_{kt})\} \qquad \text{for} \quad t = 1, \ldots, T. \tag{4.23}$$

where the operating cost depends on the electricity generated, e_{kt}. Because constructing transmission lines and grid stations typically take a shorter time than power plants, we assume that such auxiliary infrastructures are scheduled so as to match the completion time of the corresponding power plant.

Because a power plant takes multiple years to build, similar to coal mines, we have the following ending conditions.

$$b_t^{PP1} = I^{PP} \cdot \sum_{k=1}^{K} \sum_{\tau=t+1}^{T} y_{k\tau} \qquad \text{for} \quad t = T - T^{PP} + 1, \ldots, T-1. \tag{4.24}$$

$$b_T^{PP1} = 0. \tag{4.25}$$

4.2.6 Demand Constraints

Demand constraints ensure that the total amount of electricity supplied at each demand zone is less than its energy gap.

$$\sum_{k=1}^{K} (\omega^{D_{kn}} \cdot p_{knt}) \le G_{nt} \qquad \text{for} \quad n = 1, \ldots, N \quad \text{and} \quad t = 1, \ldots, T. \tag{4.26}$$

4.2.7 Budget Constraints

The first set of budget constraints limits the total spending on energy in each year by the budget.

$$\sum_{j=1}^{J} b_{jt}^{CM1} + b_t^{CM2} + b_t^{RW1} + b_t^{RW2} + b_t^{TR} + b_t^{PP1} + b_t^{PP2} \le g_{t-1} \cdot RA_t \tag{4.27}$$

$$\text{for} \quad t = 1, \ldots, T.$$

where RA_t is the ration in year t, that is, the % of GDP allocated to the energy sector for these projects; g_t is year t's real GDP.

The second set of budget constraints connects GDP in year t, g_t, to year $(t-1)$'s energy consumption.

$$g_1 = g_0 + Coef \cdot \sum_{k=1}^{K} \sum_{n=1}^{N} (\omega^{D_{kn}} \cdot p_{kn1}). \tag{4.28}$$

where g_0 is the initial GDP and $Coef$ is the elasticity of GDP with respect to energy consumption, that is, the slope of the country or economy specific regression model with dependent variable being real GDP and independent variable being energy (electricity) consumption.

$$g_t = g_{t-1} + Coef \cdot \sum_{k=1}^{K} \sum_{n=1}^{N} \{\omega^{D_{kn}} \cdot (p_{knt} - p_{knt-1})\} \qquad \text{for} \quad t = 2, \ldots, T. \tag{4.29}$$

Specifically, GDP growth in year t depends on how much more electricity is consumed in this year than the previous year.

4.3 Solution and Impact

In this section, we present the solutions generated by the mathematical model for Pakistan and compare them to the government's plan in metrics such as cost per MWh consumed (for cost efficiency), net GDP (GDP less investment in coal-fired energy sector, for economic growth), energy gap (for energy security), and coal efficiency (coal burnt annually per MWh consumed, for carbon footprint). We shall also derive insights on how an energy supply chain should be built up strategically.

We consider various scenarios of budget from 1%, 2% to 5% of real GDP, planning horizon (25 or 50 years), and demand growth rate (5% or 7%). The mathematical model leads to a large-scale multi-period mixed integer program with 9,466 constraints, 3,317 integer variables, 2,573 binary variables and 11,025 continuous variables (for 25-year scenarios). The mathematical program is solved by Gomory cutting planes method and implemented by a code written in Python ver. 2.75 and Gurobi Solver ver. 5.6. Due to the complexity of the model, an optimal solution is not always achievable. We accept suboptimal but best solutions found if the values of their objective functions are sufficiently close to those of the optimal solutions or a certain limit of running time is reached. All computations are done on a desktop computer with an Intel Xeon 2620 2.0 GHz and 20 GB RAM. The computing time ranges from 4 minutes to 1,344 minutes. Table *4.5* summarizes CPU times and optimality gaps for the scenarios discussed in this section.

Demand Growth	**Planning Period of Time**	**Ration (% of GDP)**	**Optimality Gap (%)**	**Running Time**	**Type and number of Variable**
5%	25 years	1%	4.9937%	216.11 sec	Variable Type: 11,025 continuous, 3,317 integer (2,573 binary)
		2%	7.5839%	3,315.00 sec	
		3%	8.6058%	29,678.00 sec	
		4%	0.8686%	4,288.95 sec	
		5%	9.2671%	667.37 sec	
	50 years	1%	8.5173%	5,718.00 sec	Variable Type: 23,711 continuous, 7,093 integer (5,497 binary)
		2%	11.8825%	26,218.00 sec	
		3%	20.9940%	80,633.03 sec	
		4%	7.8265%	19,247.00 sec	
		5%	4.4076%	10,285.73 sec	

Table 4.5: CPU Time & Optimality Gaps

The mathematical model provides intriguing solutions, which are drastically different from the government's plan. Recall that the government's plan explores only the largest reserve at Thar and builds all power plants at that location. For comparison, let's consider a representative scenario with 5% demand growth, annual budget of 3% of GDP and a planning horizon of 25 years (see *Figure 4.4*). The optimal solution first mines the smallest reserve in Salt Range (in the north) near the largest demand zones (the industrial hub in Punjab) that require much less time and capital to setup than other reserves. The medium reserve at Sonda/Lakhra (in the south) near the commercial hub in Sindh is next explored, but the largest reserve at Thar (in the southeast corner) is not setup for mining throughtout the planning horizon in this scenario. Power plants are first built at the largest demand zones in Punjab and supplied locally by the Salt Range mine so as to minimize the yield loss at an affordable coal transportation cost. After the medium reserve at Sonda/Lakhra is setup, power plants are then built at demand zones in Sindh and supplied locally by the Sonda/Lakhra mine. When the Salt Range mine runs out (it depletes in about 20 years in this scenario), the power plants in Punjab shall switch supply from Salt Range to Sonda/Lakhra in Sindh. Power plants may be built at coal reserves after nearby demand zones run out of space.

Figure 4.5 illustrates how the optimal solution supplies and reduces energy gaps at demand zones in this scenario. Electricity is first supplied to the demand zones in Punjab, and then to demand zones in Sindh soon after. In about 23 years, the optimal solution reduces energy gaps at all demand zones to zero, and it remains that way till the end of the planning horizon. We must point out that energy gaps may not reduce to zero in other scenarios with smaller budgets and/or higher demand growth rates.

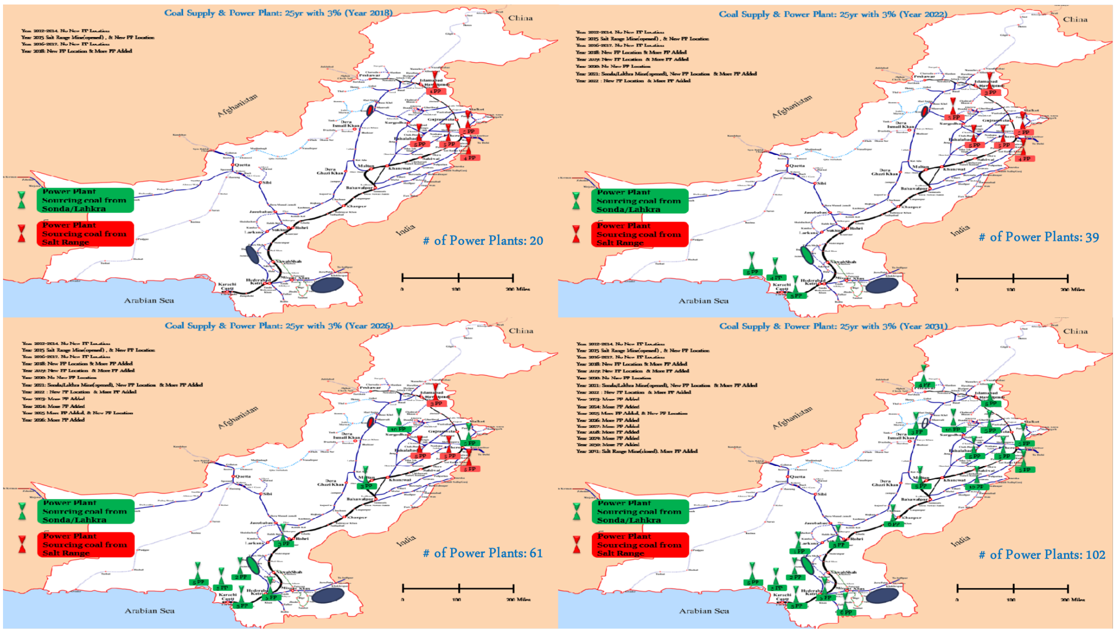


Figure 4.4: The optimal solution on reserve selection and power plant locations for the scenario with 5% demand growth, a budget of 3% GDP and a 25-year planning horizon. Circles - coal reserves; empty circles - reserves that run out; collate shapes - power plants (the box below indicates the number of power plants in service).

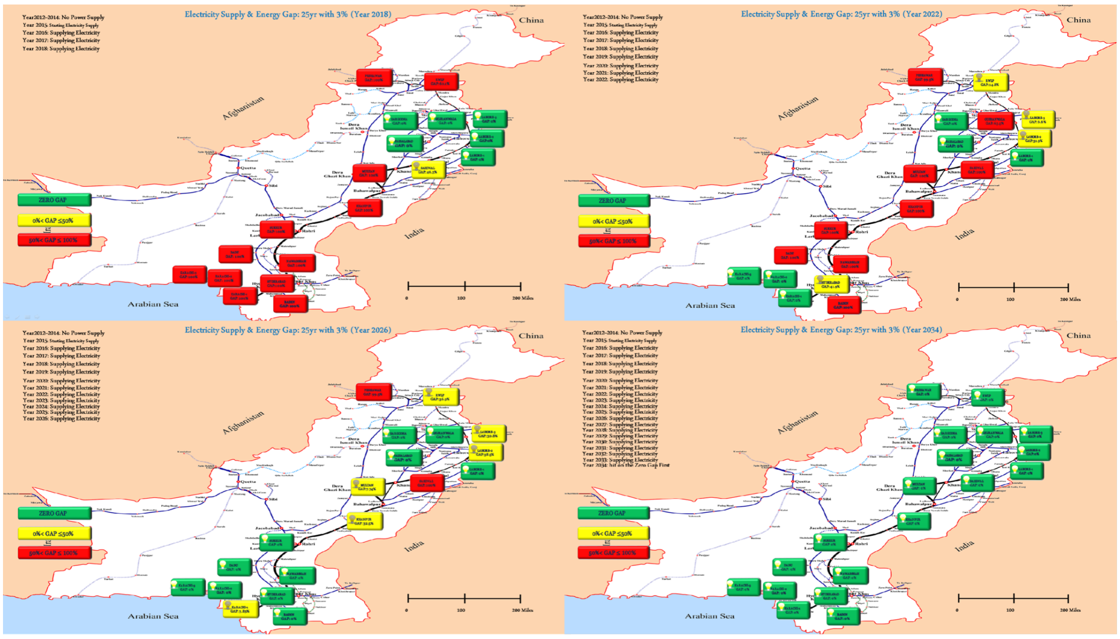


Figure 4.5: The optimal solution on transmission and energy gaps at demand zones for the scenario with 5% demand growth, a budget of 3% GDP and a 25-year planning horizon. Green - 0% gap, yellow - 1% to 50% gap, red - 51% gap and above.

The unique features of the energy supply chain play critical roles in shaping up the optimal solution. Specifically, power plants are first built at demand zones until the limit on the number of power plants is reached. This solution is driven by the *yield loss* as power plants are more expensive to build than railways. Despite the limited reserve at Salt Range, the optimal solution explores it starting from the beginning because of the *dynamic interaction* between energy consumption and economy. Although Salt Range has the smallest reserve, it is inexpensive and fast, and also close to the largest demand zones. In contrast, Thar has the largest coal reserve but it is not only remote from all demand zones but also requires the highest investment and longest time to set up the mining infrastructure. Intuitively speaking, "distant ocean cannot put off a nearby fire." Although the Salt Range reserve does not last for ever (and so we must be mindful about reserve switch down the road), it can jump start the energy supply, which, in turn, fuels the economy and leads to a higher investment back to the energy sector in the future (to explore, for instance, the Thar reserve). Doing so can help turning the vicious energy-economic cycle into a prosperity cycle. Thus the capital spent to set up Salt Range is not a waste but a worthy investment.

To quantify the impact of our model and solutions, we compare the optimal solution to the government's plan for this scenario (5% demand growth, a budget of 3% GDP and a 25-year planning horizon) on four metrics (*Figure 4.6*): cost efficiency, i.e., cumulative cost over cumulative MWh (a), net GDP (b), country-wide energy gap (c) and coal efficiency (d).

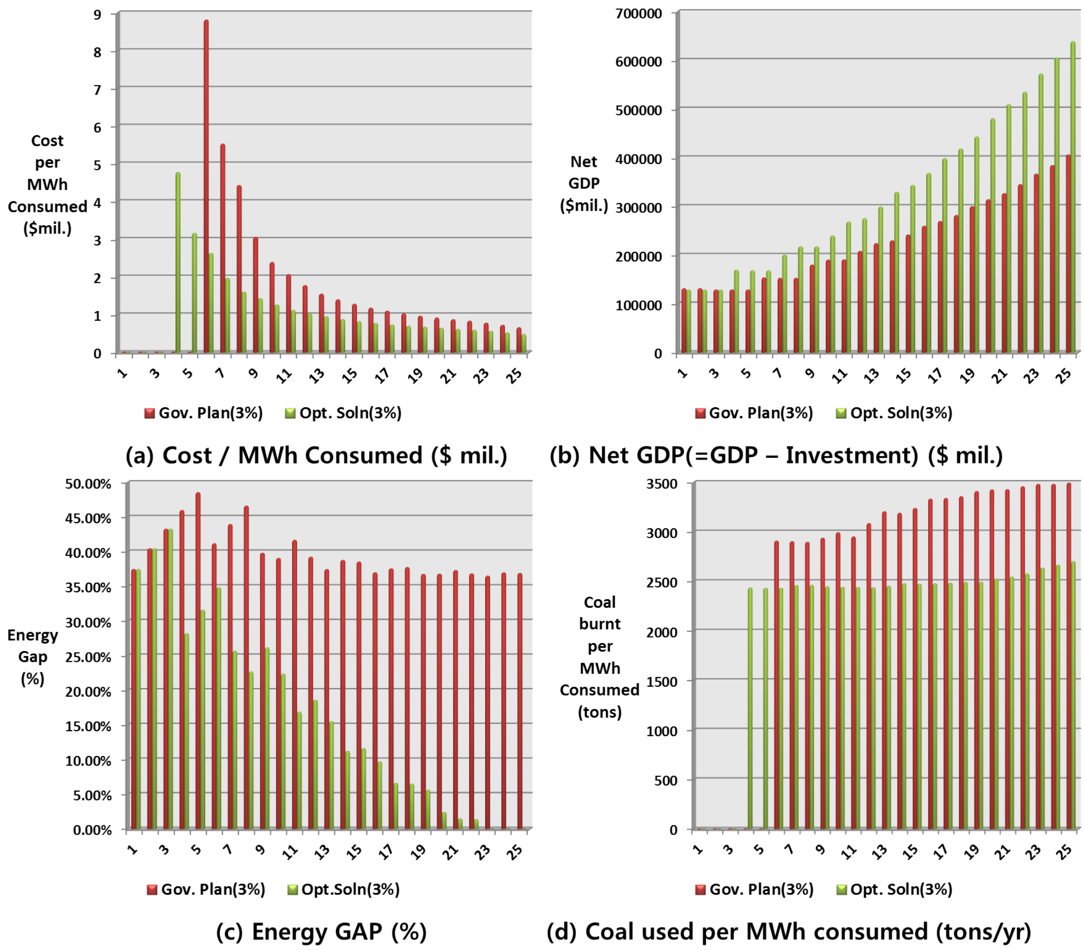


Figure 4.6: Optimal solution vs. Government's plan.
X-axis: 25 year time horizon for 5% demand growth & 3% ration.

As we can see, the optimal solution significantly outperforms the government's plan by spending much less for each MWh consumed (*Figure 4.6a*), boosting the economy much stronger (Figure 4.6b), reducing the energy gaps much faster (*Figure 4.6c*) with less coal burnt per MWh consumed (*Figure 4.6d*). The optimal solution delivers much more electricity to the demand zones with a higher coal efficiency than the government's plan, and thus it is more sustainable in the sense of economy and environment. Specifically, the optimal solution can reduce the energy gap down to zero in about 23 years while the government's plan maintains an approximately 36.92% energy deficiency towards the end of planning horizon. Consequently, the optimal solution will generate a net GDP in the 25th year of $639 billion, as compared to $406 billion of the government's plan. Finally, for every MWh consumed, the government's plan requires 2,898-3,496 tons of coal annually but the optimal plan only requires about 2,439-2,702 tons.

In other budgetary scenarios of 5% demand growth and 25-year planning horizon, the solutions stay qualitatively the same. The most notable difference between the scenarios with less than 3% rations and the scenario with 3% ration is that in the former, we do not have enough money to reduce the energy gap to zero. For instance, in the scenario of 1% GDP, the energy gap will rise in both the optimal solution and the government's plan to 65% and 70% respectively in 25th year. Interestingly, the optimal solution still significantly outperforms the government's plan on the net GDP ($228 billion vs. $195 billion) and coal efficiency (2,437-2,461 tons vs. 2,744-2,876 tons annually per MWh consumed). In the scenario of a 2% GDP, the energy gap will rise in the government's plan to about 53% in the 25th year but decrease in the optimal solution to around 36%. Consequently, the optimal solution outperforms the government's plan on the net GDP ($412 billion vs. $305 billion) in the 25th year. In scenarios with more than 3% rations, the optimal solution will reduce energy gaps to zero much sooner than the government's plan with higher net GDP and coal efficiency. Thus, our model can be used to justify the budget required to bring down the energy gap to zero in targeted years. Increasing the planning horizon from 25 years to 50 years does not change the trend of the energy gap, net GDP and coal efficiency in all scenarios but widen the differences in the net GDPs (especially in scenarios with less than 3% rations). In addition, the optimal solution may explore Thar after the 25th year mark.

The improvement on GDP made by the optimal solution relative to the government's plan is affected by the budget. *Figure 4.7* shows the average GDP per year (in $ million) under the government's plan and the optimal solution for various budgetary conditions (% of GDP). The figure shows that although the optimal solution always outperforms the government's plan, it makes the greatest difference on the average GDP when the budget is neither too tight nor too generous. Intuitively, if the budget is very tight, it allows little flexibility for the optimal solution to improve; if the budget is very generous, cost efficiency as achieved by the optimal solution becomes relatively unimportant because funding is abundant.

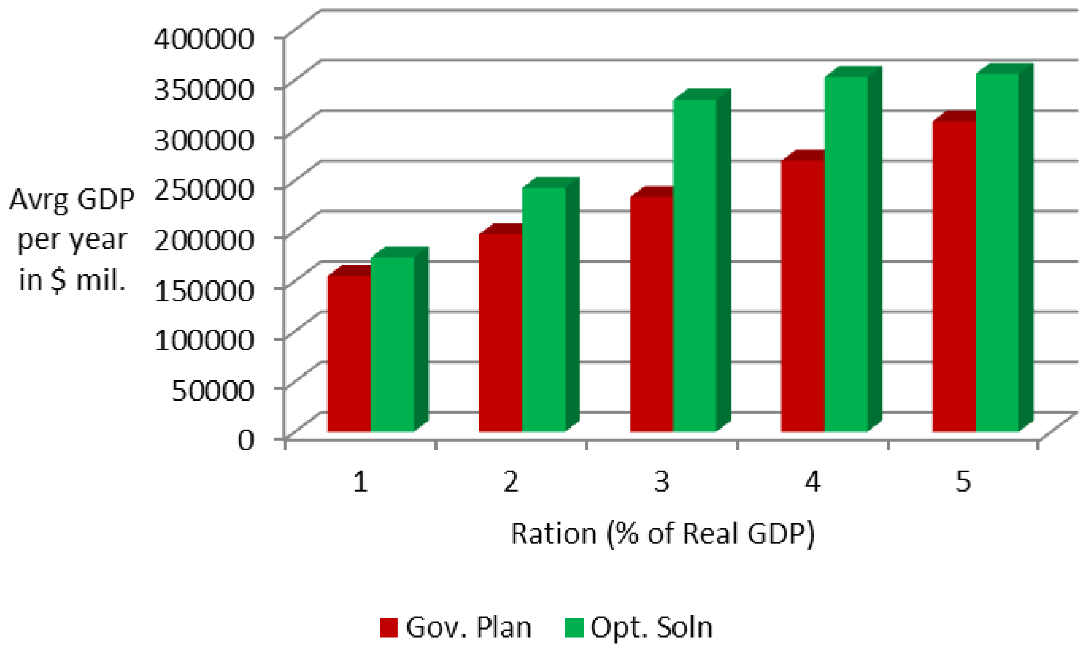


Figure 4.7: Comparing average GDP between government's plan and the optimal solution for various budgets. 5% demand growth and 25-year plan horizon.

For scenarios under 7% demand growth rate, we find, as expected, that a higher budget is required to reduce the energy gap to zero, although the optimal solutions and other insights remain qualitatively the same.

Implementation of the solutions in Pakistan is challenging and time consuming due to politics played by provinces, meager budgetary conditions and long construction cycle times. In fact, the government's plan was a political decision because the Sindh province in the south wanted to boost its economy. The Punjab province in the north was suffering and wanted to explore the smallest nearby reserve at Salt Range but was concerned about the waste of exploring a limited reserve that may soon run out. Our model and solutions came in handy to support such a strategic move of Punjab and is also in the interest of Sindh as both the small (in Punjab) and medium (in Sindh) reserves are recommended. According to press media reports (The News International 2014), Punjab province has started exploring the nearby reserve at Salt Range and building coal-fired power plants close to demand zones, as indicated by our solutions.

4.4 Conclusion

Energy deficiency and economic crisis are correlated and commonplace in developing countries. One key to solving the energy deficiency in these countries lies in the design of energy supply chains. An energy supply chain has unique features that distinguish it from the well-known logistics networks, such as, yield loss of power transmission, limited reserves that may run out, and a strong interaction between energy consumption and GDP. In this research, we construct a novel mathematical model to capture these unique features of energy supply chains. Through a real life example of Pakistan, we demonstrate the potential of the model in breaking the downward energy-economic cycle and ensuring energy security, economic prosperity and sustainability.

There are few limitations of this research. First, our model suggests a large number of power plants to be built at coal reserves (mines) however, such a huge number only shows the possibility of satisfying the future energy needs of the country. In actual, as we assume business as usual (BAU) energy options other than coal that means other energy resources can contribute to the energy mix of country and in real life we do not need to build so many power plants at coal mines.

Second, a heavy traffic of coal trains can potentially bottleneck the railway network as the supply of coal will eventually shift to large reserves (Thar and Sonda/Lakhra) located at southern part of the country whereas the major demand zones are located in the northern part (Punjab). Third, too much reliance on electricity generated through coal can pose a serious challenge on security, maintenance and environmental issues.

Chapter 5

Sustainable Energy Supply Chain

This chapter addresses sustainability issues of coal energy supply chain. The research presented here aims to provide a broad guideline on economic, environmental and social dimensions of sustainability. Since energy policy is multifaceted and context dependent therefore, the scope of this dissertation is aimed at a balanced usage of coal as per world average for electricity generation. This dissertation does not provide an exact "solution" to the energy crisis as electricity is generated with a mixture of all available fuel options which cannot be covered within the scope of this dissertation. In this essay, it is assumed that a transition to a coal based economy is desirable to reduce the dependence on foreign oil imports.

This chapter is organized as follow; in *section 5.1* literature review of sustainable energy supply chain is presented with the identification of existing literature gap in social and environmental dimensions. The need for this kind of study is realized to focus on energy crisis situation of the country with the flexibility of context based selection of energy indicators for sustainability analysis.

In *section 5.2*, sustainable energy requirement in relationship to the economic growth is analyzed. Key indicators for economic sustainability are identified as, diversity of energy supplies, availability and affordability, continuous supply and vulnerability to foreign threats.

Environmental analysis discussed in *section 5.3* used EIO-LCA, economic input output life cycle analysis, to analyze environmental impact of coal as a fuel for electricity generation. GHG emissions portfolio of the country along with suggestions to control these emissions are discussed in this section.

Ecological system theory is used in *section 5.4* to understand the context of energy crisis and the interacting systems in which government, policy makers, power generation units, administrative units and individuals exist. To the best of our knowledge, this approach is novel and has never been used to explain social aspect of sustainability in literature. The chapter is finally concluded in *section 5.5* with a brief summary of results.

5.1 Sustainable Energy Supply Chain

World Commission on Environment and Development (1987) defines sustainable development as *"development that meets the needs of the present without compromising the ability of future generations to meet their needs"*. Energy planning and policy makers are required to outline sustainable energy policies focusing on identification of supply and demand, strategies to tackle the increase in energy demands, increasing the efficiency of existing energy resources, diversification of fuel mix, energy security and focus on environmental issues related to energy production and usage through the development of renewable energy resources. According to OECD (2001), sustainable energy policy measures include development of renewable energy, efficiency improvement of energy systems and transfer of cleaner technologies to developing countries.

Christopher (2011) mentioned the impact of fossil fuels (oil) on energy supply chains as: *"When many of today's supply chains were originally designed, the cost of oil was a fraction of what it is today"*. Similarly Halldorsson and Kovacs (2010) highlighted the context in which today's supply chains have been designed and implemented; that is mainly towards industrial sector with abundant sources of energy (fossil fuels) available and confirmed that the impact of these reserves are not properly addressed in literature.

The current issues faced in energy supply chain are different with new dimensions including scarcity of resources, selection of best available option for diversification and energy security. As argued by Buffard and Kirschen (2008) the vulnerability of the current centralized energy supply infrastructure with events like terrorist threats, natural disasters, geopolitical disruptions, aging of complex infrastructure, impact of greenhouse gases emerging from thermal power plants and regulatory and economic risks are the factors which are posing new challenges and require a well defined sustainable energy supply chain.

According to Rogers, Kelly, Rogers and Carter (2007), accessibility of fossil fuels still make these fuels economically feasible over alternative energy sources and *"access to plentiful and inexpensive fuels has been an important part of building successful supply* *chains"*. For countries with conventional energy reserves (oil, gas and coal) still rely heavily on thermal energy resources to meet the energy needs; the question becomes really intriguing and needs further investigation on the development of a sustainable energy supply chain that addresses environmental issues due to the use of conventional energy sources.

There has been a long debate and increasing pressure on government policy makers to shift electricity generation fuel mix of the country from heavily dependent oil and gas towards indigenous coal reserves due to prevailing electricity crisis. In past, several attempts have been made to devise a strategy for these reserves. However, due to fragile economy and lack of infrastructure for utilization of these reserves no concrete strategy is formulated to date. In first half of dissertation, we have provided a guideline on how to develop coal based energy supply chain gradually with limited budget. This essay analyses concerns related to the sustainability issue of coal energy supply chain.

From sustainability point of view, utilization of coal for electricity generation or for other energy usage has always been under criticism due to its environmental impact. These kind of issues have been addressed in sustainability literature from developing countries perspective like Pakistan, where the sustainability discussion is more focused on economic and social domain, while in developed countries this discussion is directed towards environmental topics.

For GOP (government of Pakistan) the key concern is to draft such an energy policy that addresses the ongoing electricity crisis of the country in a way that provides a comprehensive plan on sustainable utilization of these coal reserves for future energy security of Pakistan. The decision of utilizing these huge reserves seems the right choice to reduce dependence on oil imports, depleting gas reserves and seasonal fluctuations in hydro sector.

It has been argued for long that coal should be used as a primary source for electricity generation to fulfill electricity shortage crisis. Kessides (2013) analyzed the grievous situation that Pakistan economy is facing due to electricity shortages and proposed aggressive utilization of coal reserves for a better balance in the energy mix as perhaps the only option for the long-term energy security of Pakistan. Wang, Feng and Tverberg (2013) advocated the same approach for China, proposing coal as the primary source of affordable energy for China as coal accounts for more than 76.5% of China's energy production and about 68.0% of its energy consumption in 2010 making it far more important than oil, gas and other energy resources. Brathwaite, Horst and Iacobucci (2010) suggested using coal option as a replacement for oil due to vast coal reserves in United States. Currently coal generates approximately 50% of the electricity on the US national electric grid.

Moreover, extraction of coal is relatively cheap as compared to natural gas or oil exploration. As a low price commodity, coal prices are stable as compared to the prices for natural gas or oil. As noted in sustainability literature, the concept of sustainability should not be considered as a remedy to a problem rather it is considered a strategic move to address current and future scenarios.

5.1.1 Sustainability Indicators

The identification of indicators for sustainable energy supply chain to capture significant links within the scope of the problem is of critical importance. There are number of energy indicators (IAEA, UNDESA, IEA, EUROSTAT, EEA, 2005 and EEA, 2006) available depending on the context of the problems analyzed. A common problem with sustainability energy indicators is that there are no widely accepted indicators for social dimension. The problem with social indicators is the inability to have a quantitative measurement of these indicators as compared to characteristics of the indicators that are defined to analyze economic and environmental aspects of sustainability.

International Atomic Energy Agency (IAEA) identified a list of thirty different indicators for sustainable energy development (IAEA, 2005; Vera and Langlois, 2007; Vera, Langlois, Rogner, Jalal and Toth, 2005) with the consideration of economic, social, environmental and institutional dimensions. The main question is not in defining these indicators of sustainability but the major challenge lies in customization of these indicators in contextual circumstances and the way in which they are integrated.

As we note from Kemmler and Spreng (2007), there is no standard methodology that explains how to define energy indicators. Although few researchers (Hardi and Zdan, 1997; Meadows, 1998 and Bossel, 2003) have provided some guidelines related to this issue. Moreover, energy indicators identified for social, economic and environmental aspects need to compliment each other and create a balance that carries equal weight for each dimension of sustainability (Kemmler and Spreng, 2007).

The objective for the development of a sustainable energy supply chain for Pakistan is to ensure that indigenous coal reserves are utilized for electricity generation. The whole energy supply chain needs to be re-evaluated, as the current contribution of coal is only 0.2 percent. Therefore, with the decision to use coal reserves, the logical question about the sustainable use of these reserve arises that needs to be addressed through the proper selection of indicators that monitor carbon emissions from energy sector, energy security, diversity, economic growth and the social impact of electricity on lives of masses suffering from electricity shortages. These indicators can provide means to energy policy makers to monitor specific goals set by the country and communicate to further improve for a more sustainable development.

Indicators for economic dimension include electricity intensity, energy security, accessibility and affordability. For environmental aspect indicators like GHG emissions, air and water pollution and land usage are identified. For social dimension, ecological systems theory is used to understand dynamic interaction that exists between government, electricity infrastructure units (electricity generation, distribution and transmission units) and society.

The indicators selected above are based on in depth analysis and understanding of authors about the problem of energy crisis of Pakistan. Indicators for economic, environmental and social aspect are assumed to have a causal relationship in the current energy supply chain. Sustainable energy supply chain is not a one-time fix rather it is strategic planning that can bear fruit only if economic, social and environmental aspects are analyzed in an integrated framework. An important point to consider is that these indicators are based on the criteria where the transition of electricity generation fuel mix on indigenous coal reserves is desirable under current technological scenarios and global trends that are observed in the world. A revolutionary change in technology or discovery of new energy source in the country will definitely require revisiting the proposed analysis.

5.2 Economic Analysis

Economic dimension of sustainable energy supply chain identifies how production of electricity through coal can help in economic development through the analysis of indicators identified as electricity intensity, accessibility, affordability and energy security. As of today, practically no substantial amount of electricity is generated through coal, therefore this analysis takes into account the economic aspect of availability of electricity and the cost comparison of electricity generated from coal to other available options for electricity generation.

According to a report by Institute of Public Policy (2009), the economic cost of load shedding during 2008 is estimated as "Rs. 210 billion or over 2% of GDP, over US$ 1 billion of export earnings and potential displacement of 400,000 workers. Costs could be higher if impact on other sectors like agriculture and services are allowed for, which account for almost the same share in power consumption as industry". Industrial sector is the second largest consumer of electricity with 28% share in 2008 suffered around Rs. 107 billion in the form of direct and indirect costs including lost production, overtimes and alternate arrangements for power. In a recent report of IPP (Institute of Public Policy, 2013) cost of load shedding to economy in year 2011-12 is estimated at Rs. 1272 billion that is equivalent to 6% of the economy.

Large scale manufacturing sectors like textiles, chemicals and fertilizer industries have arranged alternative energy generation systems (gas power plants, furnace oil generators etc.) on their own to meet export orders and keep production going during electricity load shedding hours. However, for small and medium scale industrial units including cottage industry are among the severely affected sectors as they are not financially sound to generate electricity on their own and are dependent on government.

According to several studies, electricity generation thorough coal is cheaper as compared to gas or nuclear. In some cases cost is even comparable to hydro electricity generation. To put things in perspective, according to the International Energy Agency, coal-based electricity is on average 7% cheaper than gas and around 19% cheaper than nuclear energy. The cost advantage of coal is even greater in comparison to renewable energy resources and the gap does not get much smaller when the current costs of emitting CO_2 are internalized in the general cost of producing electricity from coal. In fact, IEA and the European Commission report price ranges of \$56 to \$82 per MWh for coal-based electricity, \$50 to \$156 for onshore wind and around \$226 for solar photovoltaic.

5.2.1 Energy Security

Energy security is the root of economic growth and basis for the analysis of economic aspect of sustainable energy supply chain. According to Barton, Redgwell, Ronne and Zillman (2004) "energy security is a condition in which a nation and all, or most, of its citizens and businesses have access to sufficient energy resources at reasonable prices for the foreseeable future free from serious risk of major disruption of service". As per definition by IEA "energy security is the uninterrupted availability of energy sources at an affordable price". The concept of energy security is multi-dimensional and is discussed from different analytical perspectives.

The authors have identified following key aspects of energy security consistent with economic sustainability that lies within the scope of this research including *1) diversity of energy supplies, 2) availability and affordability, 3) continuous supply and, 4) vulnerability to foreign threats.*

1. *Energy diversity*: Energy diversity is a important element that needs to be considered while formulating the energy policy for a country. Key element of diversity includes dependence on available indigenous energy resources. Governments, while formulating energy policy give preference to the indigenous resources over imported fuels. There are examples related to energy policy followed by UK that relied heavily on domestic coal for power generation and France reliance on nuclear energy. Although these examples are the extreme measures of dependency on domestic fuels and do not justify the concept of energy diversity as a whole but still the notion holds of independence from imported fuels.

   For Pakistan, there are quite a few available options for energy diversity including, hydro, natural gas, coal and renewable energy resources. During 1970, the fuel mix for electricity generation was well balanced on domestic natural gas reserves with approximately equal share from hydro (*Figure 5.1*).

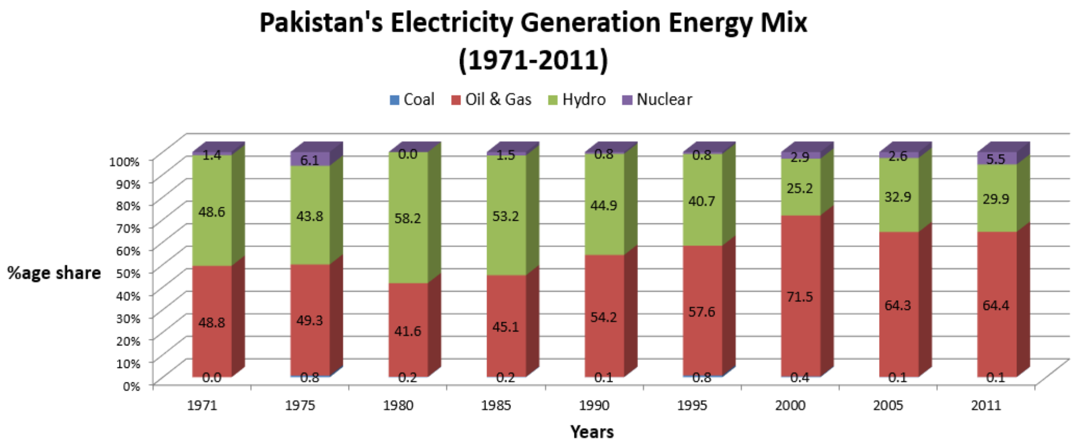


Figure 5.1: Energy mix history

Due to the poor planning of GOP natural gas resource was not used sensibly and the reliance on imported oil for electricity generation increased as no major initiative was taken in hydro sector. During 2005-2011, share of gas declined due to depleting gas reserves as well as share of hydroelectricity dropped due to seasonal variations and construction of dams by neighboring India that resulted a decline in available water reserves for electricity generation.

Despite the fact that Pakistan has large coal reserves discovered in 1993, which can last for next few centuries, more emphasis was on natural gas utilization that later on proved to be expensive due to shortage of gas reserves and more reliance on imported furnace oil for electricity generation.

As argued by Helm (2002), all sorts of policies can be justified for the sake of diversity by having mix of fuels like maintaining nuclear, expanding gas, supporting coal and renewables. For Pakistan, current energy mix for electricity generation is vulnerable to volatile oil prices as we have experienced doubling of oil prices in mid-2007 and mid-2008, that later on followed by a major decline in price in early 2009 and a more stable price level in 2009 (EIA, 2010). The impact on the Pakistan oil imports with fluctuating oil prices can be seen in *Figure 5.2*.

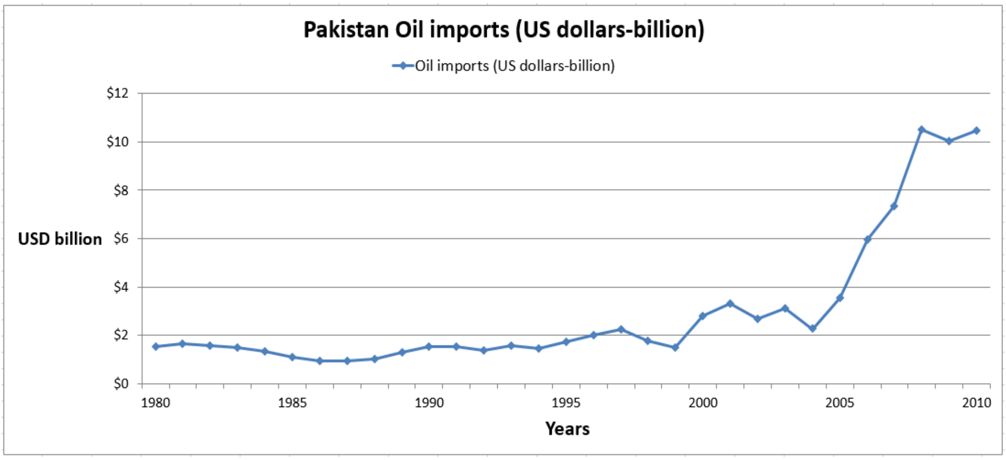


Figure 5.2: Pakistan oil imports

The analysis is consistent with the view of Klare (2007), where he mentions that part of ensuring availability entails procuring a sufficient and uninterrupted supply and minimizing foreign dependency on fuels.

2. *Affordability and availability*: Supply side economic perspectives often link energy security to stability in the energy supply, that is, stability both in quantity (availability) and price (affordability) of the energy supply. According to Intharak, Julay, Nakanishi, Matsumoto, Sahid, Aquino and Aponte (2007) energy security is defined as the "ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy". Social equity considered under the social dimension of ISED (Indicators for Sustainable

Energy Development) by Vera, Langlois et al., (2005) identify degree of fairness and inclusiveness with which energy resources are distributed, energy systems are made accessible, and pricing schemes are formulated to ensure both availability and affordability.

Availability involves the reliable and sufficient supply of energy services to consumers and businesses, while affordability looks at the cost and the volatility in cost of the energy services to consumers and businesses. Le Coq and Paltseva (2009) defined supply security as "a continuous availability of energy at affordable prices". Scheepers, Seebregts, de Jong and Maters (2007) definition of supply security is "A security of supply risk refers to a shortage in energy supply, either a relative shortage, i.e. a mismatch in supply and demand inducing price increases, or a partial or complete disruption of energy supplies. A secure energy supply implies the continuous uninterrupted availability of energy at the consumer's site". Ultimately, the goal of the economic perspective is to simultaneously ensure affordability and availability of the energy supply.

According to World Bank report approximately 67% of Pakistan population is living without electricity while remaining 33% is facing severe electricity shortage with electricity utility bills comprising of large portion of household income. Lack of electricity service (availability) affects the living condition of the poor including limited possibility of home or cottage-based industries. Due to limited income (affordability), most of the people in poor village areas are using biomass or non-commercial fuels for heating and energy needs that results air pollution and cause of fire accidents. As explained by Shammin and Bullard (2009) the spending pattern of less affluent families in developed world on energy services is around 12% of household income for the poorest quintile of households in the United States. The GINI index measures the deviation of income of a household (or individual) from perfectly equal income distribution. According to World Bank, GINI index in Pakistan was reported at 30.02 in 2008. The value of GINI index varies between 0 and 100, where 100 means a perfect inequality.

Electricity prices in Pakistan keeps on fluctuating due to oil price variations in world oil market. In order to provide relief to the masses, government is providing subsidies and below cost tariffs to keep utility bills down for poor. According to a study conducted by National Economic Research Association (1996), due to higher energy prices the cost of almost all goods and services increase as energy plays a significant role (15% approx.) towards the total cost of food processing, textiles, lumber, paper processing, chemical manufacturing, and cement production. A report from UN Economic and Social Commission for Asia and Pacific (2008) for four developing Asian economies identified the effects of energy price from 2002 to 2005 mentioned that poorer households paid 33% more for fertilizers 67% more for electricity 120% more for transportation and 171% more of their income for cooking fuels as compared to middle and upper-class households expenditures on energy.

With fluctuating electricity prices, investors find it difficult to plan for future investments in electricity generation sector of Pakistan. Pindyck (2004) mentioned the difficulty in operation of natural gas-fired plants due to variation in natural gas prices that resulted in significant increases in electricity prices in United States. Another conflicting aspect of energy security discussed by Herring (2006), which mentioned the divergence between the affordability components of energy security with other energy security criteria that might affect the choice of coal technology over solar technology due to cheap per unit cost and cost to output (MWh) efficiency.

3. *Continuous supply*: In literature energy security with focus on the continuity of commodity supplies is explored in depth (see for example, Lieb-Doczy, Borner and MacKerron, 2003; Wright, 2005; Scheepers, Martin et al., 2007; Hoogeveen and Perlot, 2007). von Hippel, Suzuki, Williams, Savage and Hayes (2011) mentioned supply-based focus of energy

   security to reducing vulnerability and to minimize economic and military impact of crisis. Creti and Fabra (2007) defined supply security and short-run capacity markets for electricity as "In the short-term, supply security requires the readiness of existing capacity to meet the actual load; supply adequacy, instead, refers to the long-run performance attributes of the system in attracting investment in generation, transmission, distribution, metering, and control capacity so as to minimize the costs of power supplies".

   Current energy policy of Pakistan does not address the issue of continuous supply of electricity on short term or long-term basis due to poor economy and lack of policy incentives for investors in electricity generation and transmission infrastructure. Lack of this aspect raises serious concerns related to energy portfolio of the country and also poses a severe threat to national security from military point of view that is fighting a war against terrorism since 2001.

4. *Vulnerability to foreign threats*: More reliance on domestic reserves like coal in case of Pakistan, will not only safeguard from oil price crisis but it will also provide an alternative that is necessary for the consumers and businesses in uncertain global political situations like 1973-74 Arab–Israeli War and Kuwait–Iraq in 1990. For energy policy makers this concern is related to the vulnerability of energy profile of a country on foreign threats. Furthermore a realistic demand and supply analysis can be carried out to plan for the economic growth, based on increasing energy supply as explained by Huber and Mills (2005) in support of increasing energy supply as a solution to have a control on energy vulnerability for better energy security.

   Few researchers (Correlje and van der Linde, 2006; Vivoda, 2009) focused on energy security with an emphasis that an increase in energy supply is necessary to reduce energy vulnerability which under current circumstances is only possible if government shift its energy focus towards domestic coal, develop infrastructure for the utilization of these coal reserves which includes development of mine infrastructure, railway network, electrical grid station, transmission and distribution network that will ensure availability of energy resource and ultimately guarantee economic growth at affordable rate.

5.3 Environmental Analysis

All energy generating technologies lead to some degree of environmental impact. In order to utilize coal reserves, environmental aspect needs a careful review, as coal is an anthropogenic source of carbon emissions worldwide. The ecological footprint will be affected by the utilization of coal reserves and this impact depends on the specific electricity generation technology and include concerns related to land and water resources, pollutant emissions and waste generation. As noted by Brathwaite, Horst et al., (2010), the true cost including operational cost are quantifiable, whereas intangible cost are difficult to quantify and can be overlooked. Stracher and Taylor (2004) highlighted the issue of environmental degradation caused by coal fires.

For Pakistan, a negligible share of 0.2 percent in electricity generation with huge untapped coal reserves needs a balance shift towards coal based electricity generation approach that can free the economy from oil dependence. Sioshansi (2007) mentioned the importance of energy efficiency and environmentally friendly strategies for a nation that is looking for the development of new energy sources.

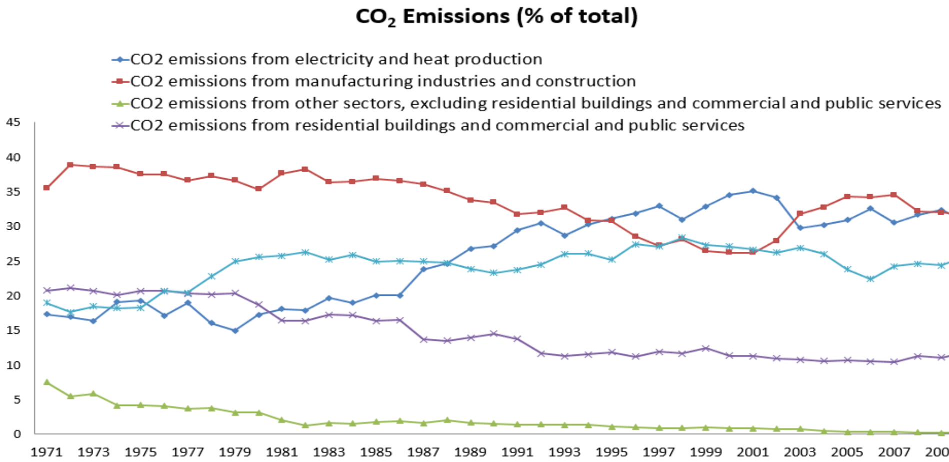


Figure 5.3: CO_2 emissions

A brief summary of carbon emissions from electricity generation, manufacturing industries and construction, transport, residential buildings and commercial and public services is shown in the *Figure 5.3*

Energy sector: Energy sector contributes a major share towards direct and indirect greenhouse gases. For the energy sector, increase in the usage of thermal resources has led to an increase in carbon emissions. The technology used for thermal power generation is not advanced and sophisticated enough which can control the release of emissions. Furthermore, due to depleting gas reserves, there is a shift from gas power plants to oil fired power plants, which contribute more in terms of GHG emissions as compared to natural gas.

Manufacturing sector: Manufacturing sector is another major contributor of carbon emissions. One of the main reasons for increase in industrial carbon emissions is related to electricity and gas load shedding in industrial sectors. Most of large units have their own gas power plants for electricity generation. Recent crisis due to depleting gas reserves, gas load shedding has pushed these industrial units in trouble.

Most of the units in the large scale-manufacturing sectors are chemical, fertilizer and textile industries with their own power generation capacity. Industrial sector is also suffered due to gas and electricity load shedding. Textile sector is the backbone of industrial sector of the country.

A huge amount of gas is required in gas industry, however, due to diminishing gas reserves textile industry was denied gas supply for 77 days in 2008-09, 95 days in 2009-10, 136 days in 2010-11, 185 days in 2011-12 and 62 days in 2012-13 up to the month December (Saeed, 2013). Most of the industrial units are now converting gas power plants to furnace oil that is not only increasing the oil import bill but also contributes more towards carbon emissions due to energy generation at industrial scale. Moreover, alternate fuels like wood, rice husk, and biomass are used as alternative fuels resulting air pollution and increase in GHG emissions.

Transportation sector: There is limited information available about the total emissions of hydrocarbons (smog and carbon monoxide), from transport sector. Increasing number of vehicular emissions from urban areas is due to the rapid growth of vehicle use in Pakistan. As reported in Economic Survey of Pakistan (2012-2013), motorcycles and rickshaws, due to their two stroke (2-strokes) engines, are the most inefficient in burning fuel and contribute most to emissions. 2-stroke vehicles are responsible for emission of very fine inhalable particles that settle in lungs and cause respiratory diseases. Two-stroke motor vehicle is a fast growing industry in Pakistan that has a growth rate of 138.6 percent in 2011-12 as compared to 2001-02. Rickshaws, motorcycles and scooter have grown by 22.2 percent and 142.5 percent over 2001-02 (see figure). With a rapid growth of this sector, there are very few hybrid cars or alternative fuels available in the market.

A careful transition from existing oil and gas reserves to indigenous coal reserves can ensure controlled GHG emissions. As previously stated, there are large coal reserves and the initiative to use coal for electricity generation can cause environmental problems. Challenge related to energy policy shift has been discussed in literature in detail. For example, Helm (2002) highlighted environmental issues as the major challenge for energy policy makers. von Hippel, Suzuki, Williams et al., (2011) identified environmental problems as the major hindrance for change. According to Glasson, Therivel and Chadwick (2013), sustainable development for future generations environmental impact assessment is required to examine environmental consequences of a development related initiative. Acid rain and global climate change are two international environment related problems that are linked with fossil fuel consumption (Asuka, 1997; Yamaji, 1997).

International agencies such as Greenpeace (2014) and the Sierra Club (2014) oppose the use of domestic coal for energy production. An inherent challenge for government is that government can reduce expensive oil imports bill along with the proper management of depleting gas reserves, which can be used more sensibly in future but it need to take care of environmental pollution that is likely to be increased with the usage of coal. However, it is assumed in this article that a transition to coal for electricity fuel mix is desirable as the prices for coal are more stable than the prices for natural gas or oil. By analyzing the dependence of imported oil and other expensive and unfeasible options available for Pakistan, a well thought off plan needs to be implemented by policy makers to mitigate the impact of environmental pollution that may be caused due to use of coal.

This paper uses life cycle assessment to examine impact of greenhouse gases on the environmental footprint when coal is used as a fuel for electricity generation. This tool has been used in literature for the analysis of environmental impacts with different fuel sources. As noted by Peter Billins, Woods and Tipper (2005), life cycle analysis (LCA) provides quantifiable data for the assessment of greenhouse gas emissions.

5.3.1 EIO-Life Cycle Analysis Tool

Wassily Leontief in 1970's theorized and developed EIO-LCA (Theory and Method EIO-LCA, 2014) based on his earlier work in 1930's for which he received Nobel Prize in Economics.

From the Input-Output accounts a matrix or table A is created that represents the direct requirements of the inter-sectoral relationships. The rows of A indicate the amount of output from industry i required to produce one dollar of output from industry j. These are considered the direct requirements – the output from first tier of suppliers directly to the industry of interest. Next, consider a vector of final demand, y, of goods in the economy. The sector in consideration must produce $(I \times y)$ units of output to meet this demand. At the same time $(A \times y)$ units of output are produced in all other sectors. So, the result is more than demand for the initial sector, but also demand for its direct supplier sectors. The resulting output, x_{direct}, from the entire economy can be written as $x_{direct} = (I + A) \times y$

This relationship takes into account only one level of suppliers, however. The demand of output from the first-tier of suppliers creates a demand for output from their direct suppliers (i.e., the second-tier suppliers of the sector in consideration). For example, the demand for computers from the computer manufacturing sector results in a demand for semiconductors from the semiconductor manufacturing sector (first-tier). That in turn results in a demand for electricity from the electricity generation sector (second-tier) to operate the semiconductor manufacturing facilities. The second-tier supplier requirements are calculated by further multiplication of the direct requirements matrix by the final demand, or $(A \times A \times y)$. In many cases, third and fourth or more tiers of suppliers exist. The supplier requirements are calculated similarly with further multiplication of the direct requirements matrix by the final demand. To determine the total output then requires a summation of many of these factors calculated as:

$$X = (I + A + AA + AAA...) \times y$$

where X(with no subscript) is a vector including all supplier outputs. The output demanded from these second-tier sectors and beyond is considered indirect output. So, includes total output, both direct and indirect.

The expression $(I + A + AA + AAA...)$ can be shown to be equivalent to $(I - A)^{-1}$, which is called the total requirements matrix or the Leontief inverse. The relationship between final demand and total output can be expressed compactly as: $(I - A)^{-1} \times y$ or $\Delta X = (I - A)^{-1} \times \Delta y$ where the latter expression indicates that the EIO framework can be used to determine relative changes in total output based on an incremental change in final demand. Typically, the values in the matrices and vectors are expressed in dollar figures (i.e., in the direct requirements matrix, A, the dollar value of output from industry i used to produce one dollar of output from industry j). This puts all items in the economy, petroleum or electricity or pickles, into comparable units.

The economic input-output analysis can then be augmented with additional, non-economic data. One can determine the total external outputs associated with each dollar of economic output by adding external information to the EIO framework. First, the total external output per dollar of output is calculated from:

$$R_i = \frac{\text{Total external output}}{X_i}$$

where R_i is used to denote the impact in sector i, and $X_i$is the total dollar output for sector i. To determine the total (direct plus indirect) impact throughout the economy, the direct impact value is used with the EIO model. A vector of the total external outputs B_i, can be obtained by multiplying the total economic output at each stage by the impact:

$$\Delta B_i = R_i \Delta X = R_i (I - A)^{-1} \times \Delta y$$

where R_i is a matrix with the elements of the vector R_i along the diagonal and zeros elsewhere, and X is the vector of relative change in total output based on an incremental change in final demand. A variety of impacts can be included in the calculation – resource inputs such as energy, electricity, or water; or environmental burdens such as criteria air pollutants, global warming gases, or hazardous wastes.

The EIO-LCA method, models, and results represent the inventory stage of the LCA. The results estimate the environmental emissions or resource consumption associated with the life cycle of an industry sector, but do not estimate the actual environmental or human health impacts that these emissions or consumption patterns cause. For example, the U.S. models estimate the emissions of particulate to the air, but do not estimate the increased number of hospitalizations or deaths due to these emissions (Hendrickson, Lave, Matthews, 2006; Hendrickson, Horvath, Joshi and Lave, 1998).

According to US Energy Information Administration (EIA) the number of pounds of CO_2 produced per kWh by a steam-electric generator for different type of fuels is given in the table shown in *Table: 5.1.*

Fuel	**Lbs of CO_2 per Million Btu**	**Heat Rate (Btu per kWh)**	**Lbs CO_2 per kWh**
Bituminous Coal	205.3	10,107	2.08
Sub-bituminous Coal	212.7	10,107	2.16
Lignite Coal	215.4	10,107	2.18
Natural gas	117.08	10,416	1.22
Distilled Oil	161.386	10,416	1.68
Residual Oil	173.906	10,416	1.81

Table 5.1: CO_2 produced per kWh with different fuel type

Most of the coal reserves of Pakistan are of bituminous and sub-bituminous type, which will result 2.08 and 2.16 lbs of CO_2 per kWh. Although natural gas is the best fuel for electricity generation among all, however, due to depleting gas reserves remaining options involves either to increase dependence on oil that will ultimately increase oil imports bill or a major policy shift towards indigenous coal reserves. Life cycle of electricity generation through coal as discussed by Spath, Mann and Kerr (1999) is shown in *Figure 5.4.*

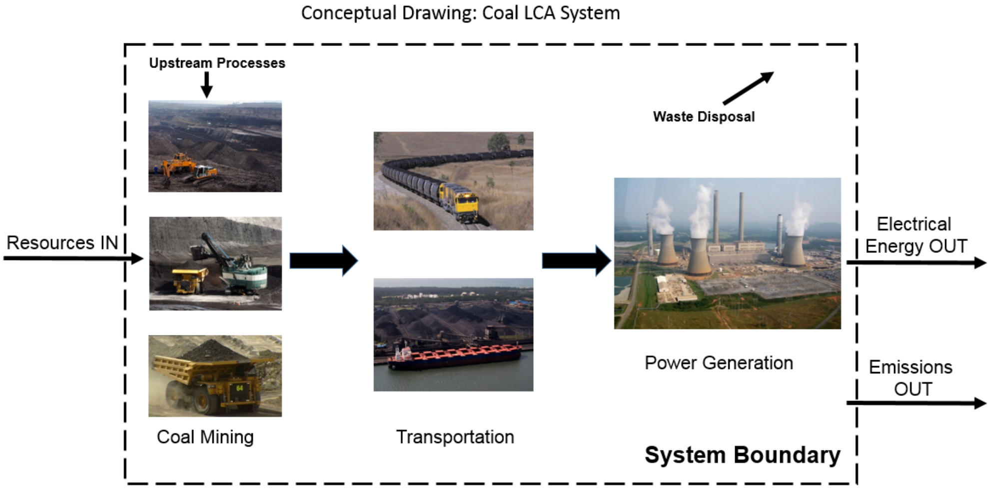


Figure 5.4: Life cycle of electricity generation through coal
Adopted from Spath, Mann and Kerr (1999)

EIO life cycle analysis tool (Carnegie Mellon University Green Design Institute, 2014) is used here to estimate greenhouse gas emissions from electricity generation through coal. The table is sorted by total CO_2 emissions. The total carbon dioxide emitted is 4240 tons - that is, due to the production of $1 million of output from the Coal Mining sector and all the economic transactions that occur between all sectors in the supply chain (direct and indirect), this much carbon dioxide is emitted. Most of those carbon dioxide emissions, 3710 t (tonnes) or almost 87 percent are emitted by the Coal Mining sector itself. Other sectors with high carbon dioxide emissions include Power generation and supply, Iron and steel mills, Rail transportation, Oil and gas extraction and Truck transportation.

Sector	Total tCO_2e ↑	CO_2 Fossil tCO_2e	CO_2 Process tCO_2e	CH_4 tCO_2e	N_2O tCO_2e	$HFC/PFCs$ tCO_2e
Total for all sectors	*4240*	*862*	*37.7*	*3330*	*9.63*	*4.06*
Coal mining	3710	419.0	0.000	3290	0.000	0.000
Power generation and supply	270	266.0	0.000	0.733	1.65	1.71
Iron and steel mills	41.5	51.7	25.6	0.253	0.000	0.000
Rail transportation	32.7	32.7	0.000	0.000	0.000	0.000
Oil and gas extraction	29.9	8.42	5.48	16.0	0.000	0.000
Truck transportation	28.3	28.3	0.000	0.000	0.000	0.000
Petroleum refineries	15.1	15.1	0.000	0.047	0.000	0.000
Pipeline transportation	10.2	4.65	0.013	5.50	0.000	0.000
Stone mining and quarrying	9.34	9.34	0.000	0.000	0.000	0.000
Support activities for other mining	6.94	6.94	0.000	0.000	0.000	0.000

Table 5.2: Coal mining activity; Greenhouse gases; Sectors: Top 10

5.3.2 Suggestions for GHG Reduction

- *Advanced technologies:* As mentioned by Katzer, Ansolabehere, Beer, Deutch, Ellerman, Friedmann, Herzog, Jacoby, Joskow, McRae, Lester, Moniz and Steinfeld (2007) new technologies promise large reductions in coal pollution. Moreover, technologies that are available today are far better from the technologies few years back. Development of such clean coal technologies for the reduction of carbon emission e.g. Integrated Gasification Combined Cycle (IGCC) can help the transition with reduced impact on GHG footprint. Furthermore, technological development in coal extraction made it relatively cheap compared to natural gas or oil production giving more opportunity to invest for carbon capturing technologies. As mentioned by Brathwaite, Horst et al., (2010), a careful analysis for the investment in clean coal technologies can make the transition feasible, however despite the potential of these technologies, their implementation must be considered carefully.

- *Efficiency improvements:* Song (2006) suggested 20% energy savings through energy efficiency improvements. Garcia and Zorraquino (2002) also confirmed about energy efficiencies of the technologies in terms of energy efficiency improvements.

In context of Pakistan electricity generation network infrastructure, efficiency and availability (uptime) for power generation plants are at alarmingly low levels (Kessides, 2013). For public sector power plants, due to lower efficiency greater amount of fuel is needed to generate same amount of power. According to NEPRA (National Electric Power Regulatory Authority, 2011), capacity utilization of public sector power generation plants during 2010-11 was around 59 percent. Furthermore, as stated above, transmission and distribution losses are at around 22 percent in comparison to countries like China at 8 percent, Korea 3.6 percent and OECD countries (Malik, 2012).

Energy efficient systems are necessary in today's market to generate more revenues at lower prices. Governments and private organizations focus toward energy efficiency as their first priority. Singapore has taken appreciable measures in maintenance and operating practices. As reported by Thavasi and Ramakrishna (2009), Singapore has considerably reduced carbon emission (15.8 percent) through energy efficiency program. The overall infrastructure can give far better results with proper maintenance and management and governance.

- *Carbon sinks:* Kyoto Protocol encourages carbon sinks as part of a country's emissions reduction commitment as carbon sinks can help to reduce carbon footprint. Forest ecosystem can play an important role in carbon cycling process as forests can capture and store CO_2 (Thavasi and Ramakrishna, 2009). For sustainable energy development, it is absolutely necessary to control carbon emissions, as energy generation is the one of the major source of carbon emission. Countries like India, Japan, China and Korea have realized this issue and have been reported with serious efforts to reduce carbon emission through the development of carbon sinks (see Lal and Singh, 2000; Wang, Saigusaa, Yamamotoa, Kondoa, Hiranob, Toriyamac and Fujinumac, 2004; Han and Youn, 2009; Zhang, Junhui, Yu, Han, Guan and Sun, 2006).

For Pakistan, a serious commitment towards afforestation is required to ensure overall carbon emission control for sustainable usage of coal. To control the environmental impact through the use of coal reserves, Pakistan government should adopt a multi-pronged approach directed towards the environmental pollution.

5.4 Social Analysis

The social dimension of sustainable supply chain is the one that is addressed least often in supply chain literature. According to Kleindorfer, Singhal and Van Wassenhove (2005), these studies and the literature as a whole have generally ignored the social component of sustainability. Specter (2008) highlighted missing link for environmental or social performance because of lack of rigorous matrices of environmental and social performance in many industries.

The authors have adopted a theoretical approach to explain social dimension of sustainability using ecological systems theory, also called development in context or human ecology. The theoretical framework helps to understand dynamic interaction that exists between government, electricity infrastructure units (responsible for electricity generation, distribution and transmission) and society (masses). This essay presents a qualitative study using Bronfenbrenner's ecological theory to understand the context of energy crisis and the interacting systems in which government, policy makers, power generation administrative units and people exist. To the best of our knowledge, this approach is novel and has never been used to explain social aspect of sustainable energy supply chain.

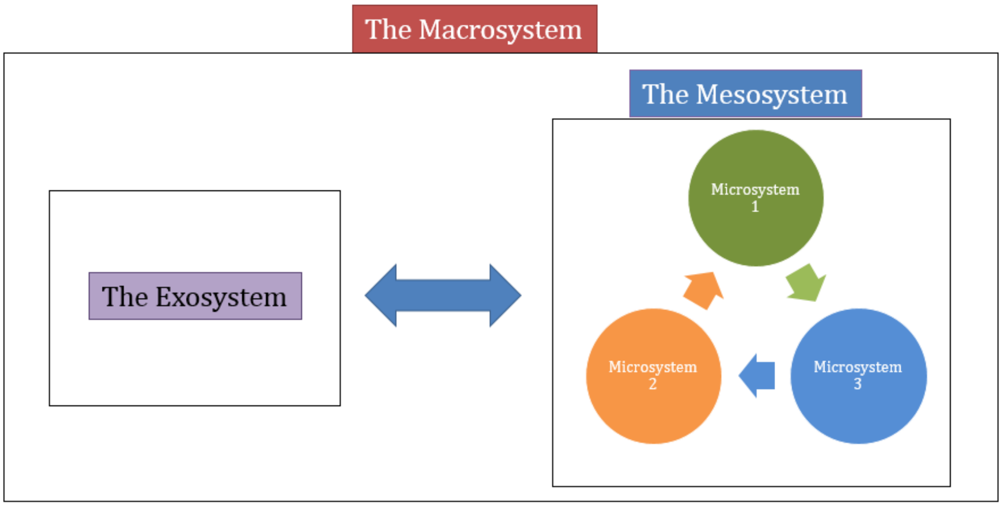


Figure 5.5: The ecological model

Ecological systems theory, also called development in context or human ecology theory identifies five environmental systems with which an individual interacts (see *Figure 5.5*). This theory provides the framework from which community psychologists study the relationships with individual's contexts within communities and the wider society. The focus of this study is individual or group of individuals in context of electricity crisis, their interaction with government administrative units and perception about government policy for electricity generation.

Urie Bronfenbrenner (1979) defined ecology of human development as *"The scientific study of the progressive, mutual accommodation between an active, growing human being, and the changing properties of the immediate settings in which the developing personal lives, as this process is affected by relations between those settings and by the larger contexts in which settings are embedded"*.

5.4.1 Discussion

Data from various sources reporting about energy crisis of Pakistan including academic journals, case study, newspapers, magazine articles and government websites was analyzed using the ecological model (see *Figure 5.6*). Multiple dimension of analysis were identified including: government concern and limitations related to electricity crisis (macrosystem); role of administrative units for electricity generation and transmission (exosystem); and the interaction of these systems with society (mesosystem). The tension between exosystem and mesosystem was a significant finding in our research. Finally the approach of the government (macrosystem) towards administrative units (exosystem) revealed some insights about the proposed ecological framework.

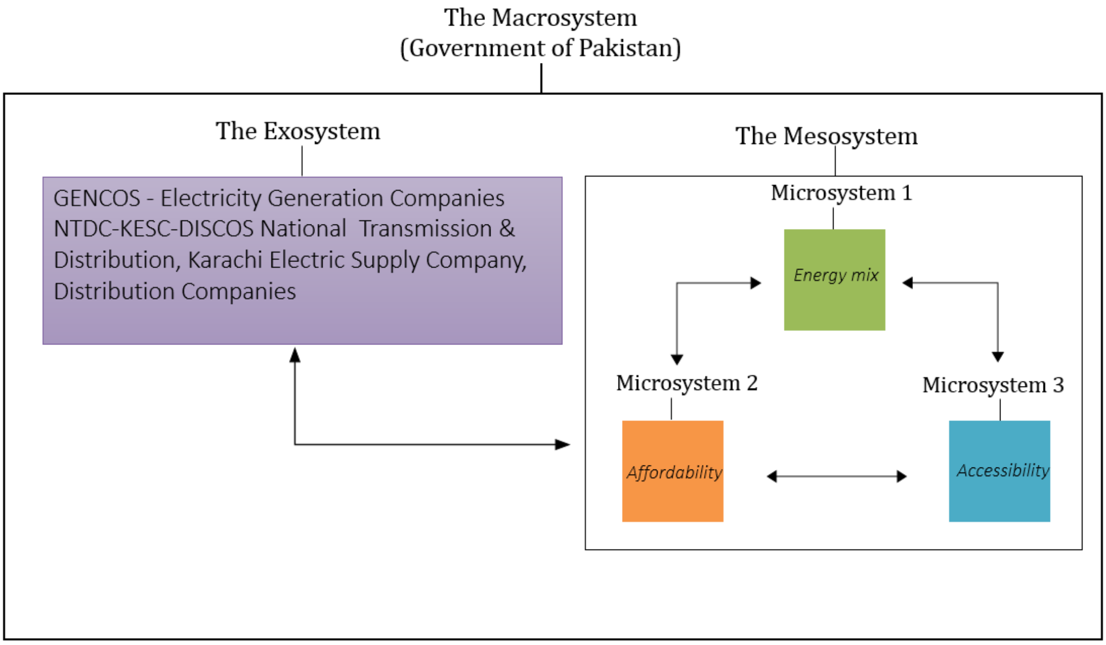


Figure 5.6: Sustainability - social aspect ecological model

- *Macrosystem:* Government decides about the energy policy that identifies the type of fuel (oil, gas, hydro, nuclear, renewable, coal etc.), share of fuel mix in electricity generation, tariffs and subsidies towards domestic, commercial and industrial consumers. There has been a history of myopic policy choices of fuel mix for electricity generation that includes excessive reliance on indigenous natural gas reserves during 1990-2000 and later on towards imported furnace oil.

  According to the energy experts, the policy shift towards coal reserves for the electricity generation is feasible. However, there is no specific policy that describes a detailed outline that how government is planning to utilize these reserves? The fruition time for coal based energy generation projects is between 3-5 years and involves heavy capital investment. Without proper planning and lack of foreign capital investment trend there need to be a well thought of plan before an attempt of policy shift.

According to the constitution, government is responsible to provide basic necessities to enable people to improve their quality of life. However, current government policies delineate an unreasonable approach from the perspective of universal standard for electricity generation fuel mix choices. Within the context of macrosystem, government policy for coal reserves needs to be analyzed along with its interaction with exosystem and mesosystem.

- *Exosystem:* The next layer of analysis is exosystem that includes electricity generation, transmission and distribution units. Distribution system is directly involved with individual and its interaction is more direct as compared to the interaction of macrosystem with individuals. The interaction of individuals with this system is influenced by the governance and policies of these units. For example, distribution system is responsible for the delivery and maintenance of the final product (electricity) and collection of bills and revenue generation and as a result experiences close interaction with an individual and society as a whole. Moreover, these units operate on policy guidelines from the government but have no role in decisions taken by the government that may include policy shift towards a specific fuel for electricity generation, tariff adjustment and subsidies to domestic consumers. This system acts as intermediary agent in the model.

  However, customers and individuals (microsystem) are directly influenced by this unit. Due to current electricity crisis, severe tension is observed in exosystem due to electricity load shedding, poor system management and maintenance (transmission and distribution losses) and efficiency related issues. This tension further extends between macrosystem (government) as these electricity infrastructure units are forced to meet the expectations of the individuals despite the fact that government policy and financial issues create an impact on the availability of services to individuals.

The management of these institutions experienced difficult times in summer due to electricity load shedding of around 8-12 hrs in cities and as a result reports or riots in major cities were observed. People started protesting on the roads and outside the administration offices. Some of these protests have also been reported violent and claimed few lives. Due to major shortfall in the system, approximately 6,000 MWh, and limited budget for the allocation of resources for electricity generation like release of oil stock from state oil department to power plants it turned out to be really difficult to control the situation. Although there are certain issues with the management and governance of this system but they do not want to be held accountable in this crisis situation.

In early 80's the policy shift from cheap hydro to expensive imported oil, reliance on depleting gas reserves, price volatility of furnace oil, industrialization, population growth and lack of investment in energy sector are key reasons for current crisis situation. Furthermore, the increasing pressure from government to meet the electricity demand as quickly as possible to meet the shortage adds on extra pressure on administrative units. Government is trying to resolve electricity crisis in without any planning while individuals/society needs electricity demands to be met without interruption and the players in exosystem are facing extreme pressure from both sides.

- *Mesosystem:* Mesosystem is a combination of all the microsystems in which an individual interacts. The microsystems identified in this study include individual's perception about the electricity crisis and government efforts towards electricity crisis situation. The microsystems in current settings include affordability, accessibility and fuel mix for electricity generation. These system often overlap and are not the only systems which can be selected but authors have identified these system based on the scope of this research.

  Consistent with the indicators for sustainable energy development for social aspect (Vera, Langlois and Rogner et al., 2005), affordability includes household income spent on fuel and electricity and household energy use for each income group and corresponding fuel mix. Accessibility included share of households (or population) without electricity or commercial energy, or dependence on non-commercial energy and total number of household population. The microsystem energy mix includes choice of fuel for electricity generation that is directly related with the cost of each unit of electricity generated.

  In mesosystem, microsystems interact and overlap between themselves. For example, the price fluctuation of electricity is directly linked with the volatile prices of oil in the world market. Due to an increasing trend in oil prices the electricity price is adjusted accordingly on fortnight or monthly basis. It directly affects the affordability of the consumers not only in terms of electricity bills but most of commodity prices are also adjusted with this change.

Furthermore heavy circular debts in electricity supply chain results into pending or delayed payment to IPPs (independent power producers) and PSO (Pakistan State Oil) as a result electricity shortfall fluctuates resulting long unscheduled load shedding hours. Electricity power generation capacity dependent on water resources face seasonal variations and the output varies between 10-30 percent which is another element of price fluctuation that directly affects the affordability and accessibility of electricity. Interaction between mesosystem and exosystem occurs at the point where consumers blame distribution companies due to long hours of electricity load shedding.

According to people, even after long hours (8-12 hrs) of load shedding electricity bills are increasing and they have no electricity at home, school and work places. As a result thousands of workers have lost their jobs and unemployment is increasing at an alarming rate with more and more people are pushed below the poverty line every year. People are frustrated as the whole economy and social infrastructure is at the risk of collapse due to severe shortage of electricity resulting into anger, rage and violent protests that sometime include damage to public and private property.

The ecological model as posed by Bronfenbrenner (1979) is an appropriate tool to understand the contexts and systems within which individuals, administrative infrastructure units, and the government responsibility and goals co-exist. The interactions between the microsystems played a large role in individual's perceptions of their experiences due to electricity crisis.

The administrative units and their operational activities makeup the exosystem, that is at the interface of both mesosystem that is influenced by public perceptions. Individuals are only concerned with the continuous supply of electricity at affordable prices and they expect these exosystem players to provide them utility service as per their expectations.

These administrative units have certain limitations and weaknesses and are bound to provide the output based on the policy choice of the government. There is also room for improvement in terms of efficiency, management and maintenance of the infrastructure to facilitate the consumers as well as to deliver what the government expects in best possible way.

Bronfenbrenner's ecological model is used here to analyze social aspect of sustainability that explains how social dimension can be understood in an integrated environment. Previous studies considered social aspect of sustainability in isolation without considering the interaction between other subsystems and the resulting perceptions that rise due to pressure and dynamic interaction.

Actually, it is the interaction that helps us to understand the complete dynamics of social aspect of sustainability. From government perspective, it is clear that an immediate relief to the individuals is inevitable through administrative units that play the role of a "Middle Man". The future lies in concrete government policies in right direction and that ensures energy security and sustainability to provide a relief to the people. One of the most promising option is reliance on its own resources (coal reserves) that require time and capital investment on government part otherwise with the current scenario electricity cost to availability equation becomes infeasible for the public and agitation can be seen on the roads.

5.5 Summary

The authors have taken a conceptual approach to explain energy sustainability from economic, environmental and social aspects. Economic analysis focused on key issues related to diversity of energy supplies, availability and affordability, continuity of supply and vulnerability to foreign threats in context of Pakistan energy crisis.

Environmental aspect adopted EIO-LCA (economic input output life cycle assessment) approach to analyze the impact of GHG (green house gas) emissions associated with coal based electricity generation. CO_2 emissions from coal mining needs careful attention through a balanced energy mix of electricity generation and use of advanced technology.

In social aspect of sustainability this essay presented a qualitative study using Bronfenbrenner's ecological theory. The ecological theory used here is a useful tool in understanding the context of energy crisis and the interacting systems in which government, policy makers, administrative units and people exist. Findings of this section include: the state's concern with the rising costs of electricity units generated through imported oil, suffering of people and economy due to electricity shortages and policy decisions regarding energy mix (the macrosystem); the administrators positions to meet the expectations of government and people (the exosystem); and the interaction between these two systems. The tension that exists between exosystem and mesosystems was a major finding related to the limitations and weaknesses of administrative units against the expectations of individuals.

Chapter 6

Future Research and Extensions

In this dissertation we studied strategic energy supply chain design in static and dynamic environment to understand unique features of this problem in context of logistic network design. Literature gap identified in this research is addressed using integrated supply chain practices for end to end energy supply chain. We demonstrated, through an extensive computational study, the strategic development of energy supply chain considering the dynamic nature of limited reserves, increasing energy gaps and the interaction among energy, economy and budget.

This study used government plan as a benchmark to gauge the performance and impact of optimal results obtained from our mathematical model. The solution, obtained from mathematical model, is drastically different from the government plan. While government considers only the largest Thar reserve that is not only remote but also has the highest infrastructure cost and requires long time for development, our solution starts with the smallest coal reserves near country's economic centers that require much less time and capital to set up. Doing so will grow the economy faster, which, in turn, will lead to more investment back to the energy sector, and allow us to mine the Thar reserve ultimately. The power plants are scattered around the country strategically so as to minimize the transmission yield loss (and thus requires fewer power plants) at an affordable coal transportation cost by considering, in advance, a potential supply switching from the smallest reserves (after they are depleted) to Thar reserve.

One interesting fact is that government has now abandoned the plan of building all the power plants at largest mine and there are few feasibility studies under consideration for other power plant locations and utilization of imported coal reserves in the beginning and later on switching to indigenous nearby coal reserves. That actually justifies our approach of using nearby smallest coal reserves to satisfy large demand zone in Punjab later on switching to large reserves.

In last section of this research, sustainability issues related to economic, environmental and social aspects are discussed in detail to identify key energy indicators to analyse the use of indigenous coal reserves for a balanced energy mix.

We suggest to continue our research in the following directions.

- *Mathematical Properties/Algorithmic Analysis:* We suggest to further explore and extend the mathematical properties of energy supply chain to find more efficient solution algorithms.

- *Energy Portfolio:* Our results can be extended to other sources of energy, such as gas, oil, hydro, solar and wind. The unique features, economics and availability of each type of energy source can expand the spectrum of research in the field of energy supply chain design. Moreover, this research can be extended to create an energy portfolio which can serve as a starting point for a balanced energy mix. It can also aid policy makers in better decision making in utilization of indigenous reserves for future energy security of a country.

- *Resource Rich, Energy Poor Countries:* This research can be extended to resource rich and energy poor countries including many developing countries, such as India, Nigeria, and Ethiopia. These countries are suffering greater energy deficiency than Pakistan. Our work can be customized to help these countries to solve their energy problems.

- *Risk Analysis:* Our research can be extended to calculate the risk and reliability analysis of proposed energy network. Major dependance on one kind of fuel for energy purpose can pose serious risk and can be vulnerable to maintenance issues and terrorists attacks.

- *Social Dimension Empirical Analysis:* The conceptual model developed in sustainability study with the use of ecological system theory to analyze social aspect of sustainability can be extended further to verify the model using empirical evidence.

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