DESIGNING ENERGY AND WATER SUPPLY CHAINS

FOR PROSPERITY

by

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ABSTRACT OF THE DISSERTATION

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Many developing countries suffer severe energy deficiencies despite their ample reserves of energy resources, - the so-called predicament of "resource rich, energy poor." A leading driver is the energy-economy cycle, where the poor economic status, inefficient utilization of limited budget, and energy deficiency reinforced each other and have led these countries into a spiral of economic downfall. How to turn this cycle around? It is a classic question but not well answered in the energy policy/economics literature and barely studied in the operations management literature.

In Essay 1, we introduce the general concept of energy supply chains and provide a detailed literature review on related studies. The concept applies to any country blessed by natural resources but lack of electricity supply.

In Essay 2, we develop a new class of mathematical models to build up coal-based energy supply chains gradually over time to resolve the paradox of "resource rich, energy poor". Specially, we provide a mathematical approach to design cost effective energy supply chains taking into account the interaction between economy and budgets and

various types of constraints arisen in fuel production, fuel transportation, power generation and transmission, and consumption. We verify the effectiveness of the approach by real life instances in some of the energy poor countries.

In Essay 3, we study the nexus of water, food, energy and flood, which are among the most formidable challenges faced by developing countries around the world (Food and Agriculture Organization of the United Nations 2014). The development of hydropower has the potential to address all these issues in the same time and thus is prioritized in the international community to reduce poverty, promote the sustainable development of the economy, and achieve the Millennium Development Goals.

In this Essay, we apply the supply chain management concept to water resource development and provide the end-to-end and dynamic perspectives (the supply chain perspectives) needed in the expansion of hydropower network for energy security, irrigation and flood control. We identify the unique features and economies of hydropower systems in developing countries and construct a new class of mathematical models to capture the nexus of these issues, explore the synergy among different development goals and maximize the overall benefit. The model links the hydropower location decisions with the distribution decisions of power and water, incorporates conflicting requirements of different sectors, and capture a new set of cost and time trade-offs on a complex, interacting and dynamic network. Applying the model to the real-life situation of Pakistan, we develop new solutions that can significantly outperform common practices in economic prosperity. Our results demonstrate the value of the supply chain perspectives in

hydropower network expansion, and provide insights on the relative performance among popular practices, such as, concentrated vs. dispersed hydropower locations, many small vs. a few large hydropower sites, and various strategies on the mix and sequence of sites with different types and capacities.

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Chapter 1

Introduction

1.1 Motivation

Energy poverty is a universal issue in a vast majority of developing nations. Eighty-six percent of people in Tanzania depend on kerosene and candles for light, which are known to be inefficient and dangerous (IFC, 2015). Moreover the lack of electricity affects at least one in three Africans. Pakistan is facing severe electricity crises and its fragile economy is in turmoil that poses a serious threat to its economic security. As reported by NEPRA (National Electric Power Regulatory Authority, 2012), some rural areas have been experiencing unscheduled load shedding and long blackout sessions up to 12-16 hrs a day. In Southeast Asia, IEA estimates that 134 million people, or 22% of the region's population, currently do not have access to electricity and around 280 million people (almost half of the region's population) rely on the traditional use of biomass for cooking (IEA, 2013).

Many of these countries have abundant natural reserves of energy sources, such as coal, oil and gas, hydro and renewal resources like solar and wind. However, they either do not have an energy infrastructure that can convert the resources into power and distribute it massively to the users, namely, the energy supply chain, or they lack of effective use of the existing energy supply chains. In comparison, the United States is the world's largest national economy with a GDP of approximately $ 17 trillion in 2012. (World Bank, 2013) And the U.S. electricity power industry had capital spending of $ 90.5 billion, accounts for 0.54% of GDP. How does Africa look? Sub-Saharan Africa made a GDP of $ 1.6 trillion, and more than $ 300 billion is required to achieve universal electricity access by 2030. According to figures from the World Bank, the six countries have averaged a combined investment of just over $ 3 billion a year in their electricity infrastructure. (Tam Harbert, 2014).

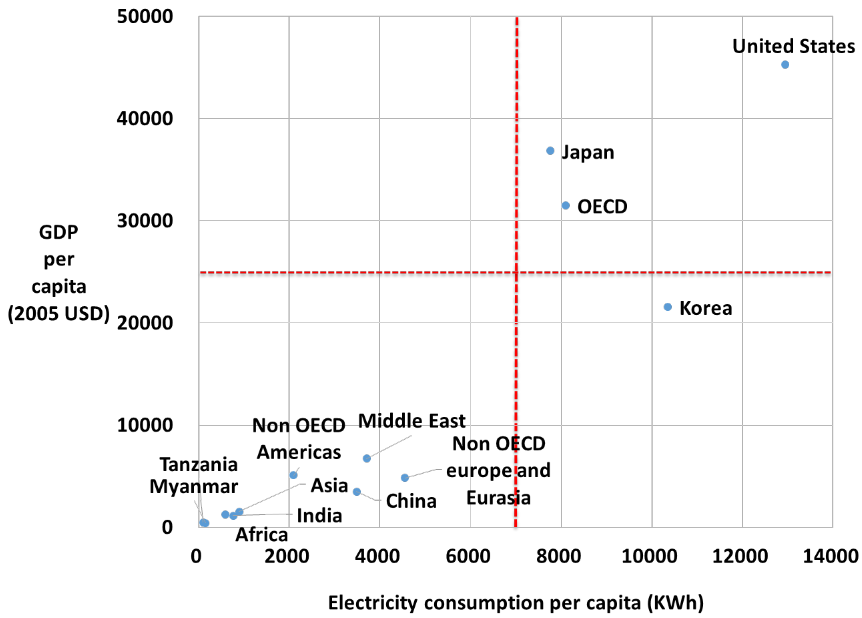

Figure 1.1: GDP per capita and Electricity consumption per capita. Units: 2005 USD & KWh. Source: IEA, 2014

Energy consumption is strongly correlated with the economic development of a country. Figure 1.1 shows that countries of OECD (developed countries) locate at the top right quadrant while undeveloped and developing countries locate at the bottom left quadrant. It is a powerful look at how economic growth affects on energy consumption.

The world energy consumption is quite disproportional to the distribution of world population. U.S. takes 4.47% of world population, yet accounts for almost 20% of world electricity consumption. Afirica are consuming 3%, yet they account for 15.39% of the world population. Similar observations can be made on non-OECD America and Asia (Table 1.1).

Region /Country /Economy	Population (Million) ,2012	Population (%)	Electricity Consumption (TWh), 2012	Electricity Consumption (%)
China	1,358.00	19.30 %	4,737.00	22.65 %
U.S.A.	314.28	4.47 %	4,069.06	19.46 %
Asia	2,320.00	32.97 %	2,071.00	9.90 %
India	1,236.69	17.57 %	939.78	4.49 %
Pakistan	179.16	2.55 %	80.13	0.38 %
Africa	1,083.00	15.39 %	641	3.06 %
Nigeria	168.83	2.40 %	26.22	0.13 %
Ethiopia	91.73	1.30 %	5.30	0.03 %
Non OECD America	467.00	6.64 %	611	2.92 %
World	7,037.00	100.00 %	20,915.00	100.00 %

Table 1.1: Distribution of The World Population and Electricity Consumption. Sources: The World Bank (2013), IEA (2014)

These disproportional distributions of electricity consumption and population are clearly displayed in the list of the 20 countries with the highest deficit in access to electricity (Figure 1.2). With respect to electricity, the global access deficit amounts to 1.2 billion people, and 87 percent of those who live without electricity are geographically concentrated in Sub-Saharan Africa and South Asia. Especially, India has by far the largest access deficit, exceeding 300 million people. Among the 20 countries with the highest deficits in access, 12 are in Sub-Saharan African countries; of those, eight report an access rate below 20 percent (World Bank, 2013).

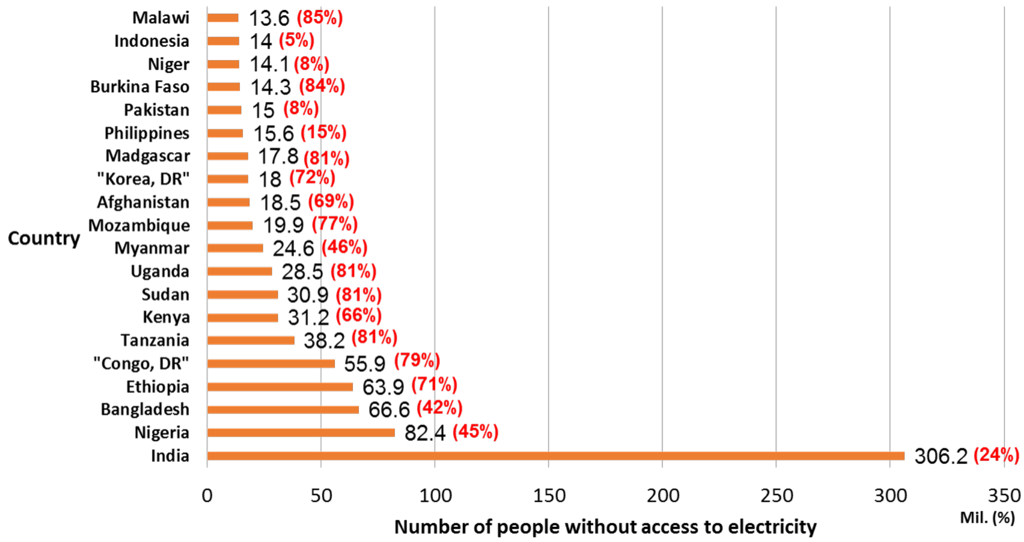

Figure 1.2: The top 20 countries where people lack access to electricity. (Unit: million) Sources: Global Tracking Framework, The World Bank (2013).

In 2013, nearly 1.26 billion indian people, accounting for over one sixth of the world's population, only generates 4.04% of world electricity. Similarly Africa has one sixth of global population, but only generates 8.63% of global electricity (IEA, 2014). Asian countries (excluding China and OECD countries), accounting for 40% of world population, but only generate 10.88% (1,464 Mtoe) electricity in comparison to the world's production of 13,461 Mtoe. Moreover, The UN expects the world to grow from 7.2 billion people today to 9.6 billion in 2050 with more than half of the extra 2.4 billion people in Africa. Currently, more than 70% population in African and Asian countries does not have access to electricity (UN, 2013, World Bank, 2013). Including India, about 1.2

billion people, have no access to electricity in the world (Figure 1.2).

1.2 Overview of Main Problems

Country	Oil Reserve (Rank) (mil. barrels)	Gas Reserve (Rank) (m^3)	Coal Reserve (mil. ton)
India	5,710 (24)	1,075,000,000,000 (26)	92.445
Nigeria	37,200 (10)	5,100,000,000,000 (9)	396
Bangladesh	28 (85)	195,400,000,000 (48)	293
Ethiopia	0.4 (100)	24,920,000,000 (74)	376
Congo, DR	1,940 (38)	90,610,000,000 (57)	88
Tanzania	0 (179)	6,510,000,000 (83)	200
Sudan	2,800 (34)	84,950,000,000 (58)	0
Uganda	1,000 (44)	14,160,000,000 (78)	66
Afghanistan	80 (76)	49,550,000,000 (66)	100
Philippines	168 (65)	108,700,000,000 (54)	316
Pakistan	313 (55)	754,000,000,000 (29)	185,000
Indonesia	3,590 (31)	3,001,000,000,000 (14)	4,968

Table 1.2: Reserves: Oil, Gas, and Coal. Source: CIA, 2013. Global methane initiative, 2010, world energy council, 2013

These energy poor countries are paradoxically endowed with immense natural resources (Table 1.2). Countries in those regions blessed to natural resource wealth aren't generating electricity enough to their people (IEA, 2013, and 2014).

Country	GDP per capita current US $	Public Debt to GDP (%)	Credit Rating (S&P)
India	1,498.9	49.6	BBB-
Indonesia	3,475.3	24.8	BB+
Pakistan	1,275.3	50.4	B-
Nigeria	3,005.5	18.8	BB-
Bangladesh	957.8	32	BB-
Ethiopia	505.0	44.4	N/A
Philippines	2,765.1	51	

Table 1.3: Budgetary condition of countries of top energy deficit. Source: CIA, 2013, Standard & Poor's, 2014

The energy poor countries typically have impoverished budgetary condition which lead to consistent inefficient investment in an energy sector (Table 1.3).

An economic growth requires an ample supply of energy (electricity); the development of the energy sector requires a significant investment, which in turn depends on the economic growth. This cross-dependence between economic growth and energy supply presents a vicious cycle (Rafique, R. and Zhao, Y., 2011). Our focus in this proposal is on breaking it by developing an innovative model to cost effectively build up energy supply chains for various resources strategically (Figure 1.3).

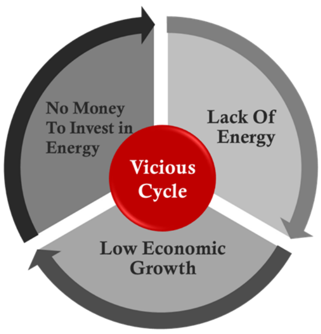

Figure 1.3: Vicious cycle

1.3 Objective and Dissertation Structure

The objective of this dissertation is to develop a new class of mathematical models to build up energy supply chains gradually over time to resolve the paradox of “resource rich, energy poor”. Specially, we provide a mathematical approach to design cost effective energy supply chains taking into account the interaction between economy and budgets and various types of constraints arising in fuel production, fuel transportation, power generation and transmission, and consumption. We verify the effectiveness of the approach by real life instances in one of the energy poor countries.

In essay 3, we study the nexus of water, food, energy and flood, which are among the most formidable challenges faced by developing countries around the world (Food and Agriculture Organization of the United Nations 2014). The development of hydropower has the potential to address all these issues in the same time and thus is prioritized in the international community to reduce poverty, promote the sustainable development of the economy, and achieve the Millennium Development Goals.

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Chapter 2

Energy Supply Chain

Energy supply chain is defined as a network of independent players collectively responsible for producing fuel, transporting fuel, generating and transmitting electricity, and cusumming electricity. (Figure 2.1)

Figure 2.1: Energy supply chain: Flow and key players

We apply the supply chain management principles to energy sector, and our objective is to synchronize all elements, such as production and transportation of fuel, generation and transmission of electricity, and consumption of electricity for achiving universal electricity access with the minimum budget.

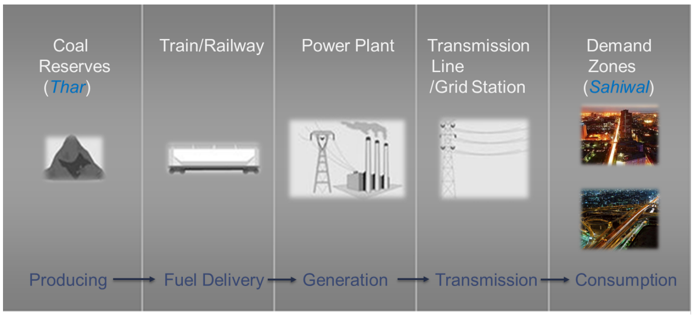
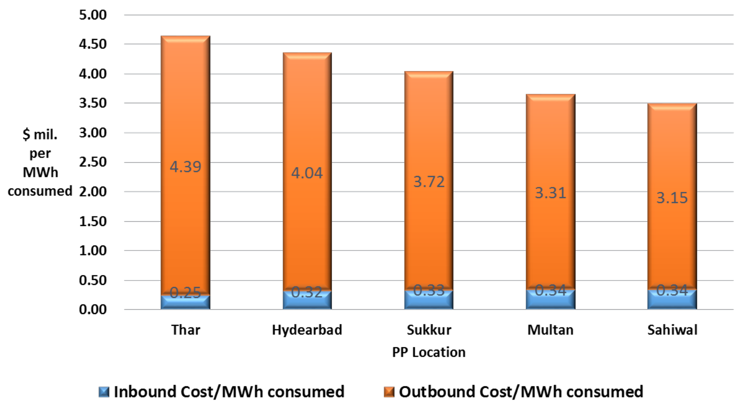


Figure 2.2: Simple Example: Coal-fired energy supply chain: Single mine location, single PP location, and single demand zone.

To develop intuition, we shall first understand how different parts of an energy supply chain may interact. For this purpose, we consider a simple energy supply chain with a sinlge mine, single power plant location and single demand zone (Figure 2.2). Through this simple example, we shall examine the impact of yield loss, the importance of a PP(power plant) location, and the importance of a mine location. The simple example is based on real-life data collected from the coal-based energy industry in Pakistan.

2.1 Key Issues in Energy Supply Chain

Yield loss may have a significant impact on the energy supply and can be a dominant fact in the location decisions of power plants. The following simple example considers *Thar* as a single mine location, and *Sahiwal* as a single demand zone. We also select a single power plant location where multiple power plants can be built. It is tested with five potential PP (power plant) locations respectively so that we can demonstrate the impact of yield loss with different distances between a PP location and a demand zone.



PP Locaiton	Thar	Hydearbad	Sukkur	Multan	Sahiwal
Distance b/t Mine and PP	0.00	1.31	3.50	6.12	6.94
Distance b/t PP and Demand Zone	6.94	5.68	3.73	1.06	0.00
Yield Loss	34.91%	29.63%	20.61%	6.35%	0.00%
# of Trains	0	3	5	7	7
# of PPs (300/500MWh)	53 (53/0)	50 (50/0)	45 (44/1)	39 (37/2)	37 (35/2)

Figure 2.3: Impact of Yield Loss on Costs and PPs (Mine: Thar reserves, Demand zone: Sahiwal, 4.5 % yield loss in every 100 miles)

If power plants are located at the coal reserve, then the yield loss is the highest (distance dependent) and so the most PPs must be built and consequently the most coal must be burnt. The cost is nonlinear because of the nonlinear behavior of yield loss (i.e 4.5% per every 100 miles). Based on the available high voltage, we here conservatively estimate the yield loss per 100 miles to be 4.5% (David Hurlbut, 2012). On the other hand, if power plants are located at the demand zone (i.e. far away from coal mines), that means the longest distance and the highest cost related to railway network. Although coal transportation cost is the highest at the *Sahiwal*, location of PPs, that has no yield loss. (Figure 2.3).

Another key issue in energy supply chain is to decide which mine to explore. The smallest mine reserve costs the least and takes less time to setup, but it has too small reserve to match the long term demand. On the other hand, the largest mine has enough coal reserve, but take more time and spends large on the setup. Therefore mine selection is important. We consider three mines that have different distances from demand zone, *Sahiwal Sonda/Lakhra* (closer to the demand zone than *Thar*), and *Salt Range* (closest mine to the demand zone). Distances between the reserves and demand zones play a major role in the design of energy supply chain (Figure 2.4).

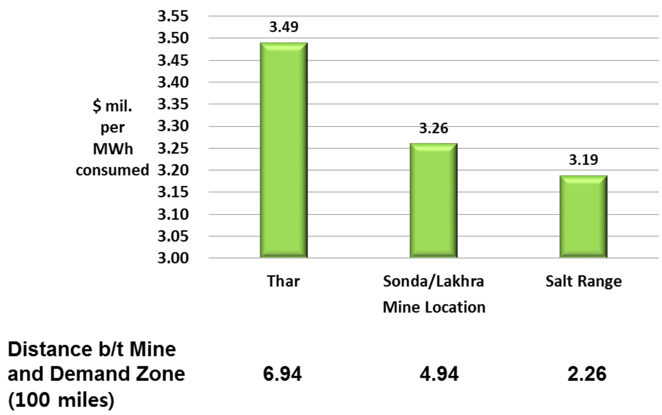


Figure 2.4: Importance of Mine Location (PP location & Demand zone: Sahiwal, 0% yield loss due to the location of PPs at demand zone)

This example shows that the energy supply chain is an integrated network whose performance in cost and electricity output depends on both of the selection of mines and the selection of power plant locations. It's necessary to consider trade-offs together.

2.2 Literature Review

Logistic networks design, integrated supply chain, Transmission system, energy economics, and energy policy literatures are reviewed within the scope of our research.

2.2.1 Design of Logistic Networks and Integrated Supply Chains

Facility location literature addressed questions to location or relocation of plants, warehouses and other facilities in a logistics network dynamically as the demand, budget and other factors change over time. Wesolowsky (1973) introduced 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 points. For a comprehensive review of facility location literature author refer the reader to e.g. Love, Morris, and Wesolowsky (1988) and Daskin, Snyder and Berger (2005).

Van Roy and Erlenkotter (1982) solved a capacitated dynamic location problem with opening and closing decisions using a dual-based branch-and-bound procedure. Mirchandani and Francis (1990) discussed discrete location theory for duality, and decomposition methods for incapacitated facility location problems. Hinojosa, Puerto and Fernandez (2000) studied a mixed integer programming model to build facilities at multiple echelons of a distribution system over time.

Canel and Khumawala (1997, 2001) solved a multi-period international facilities location problem. Melachrinoudis and Min (2000) developed a dynamic, multiple objective, mixed-integer programming model to solve the multi-period relocation problem. More related work can be found by Klose and Drexl (2005) which addressed concerns like which customers should be serviced from which facility (or facilities), Troncoso and Garrido

(2005) which considered specific production and logistics issues in the forest industry, and Dias, Captivo, and Climaco (2007) which solved a dynamic location problem with opening, closure and reopening of facilities by primal-dual heuristic approach.

The authors have extended the scope of supply chain literature to review production, inventory, and logistics decisions in an integrated framework. Min and Zhou (2002) provided guidelines for the development and implementation of these kinds of supply chain models. Chen and Paulraj (2004) suggested to analyze interrelationships of various supply chain initiatives and constructs, direct or indirect mediating effects of these activities and constructs on supply chain performance. Hinojosa, Puerto and Fernàndez (2000) studied dynamic two-echelon multi-commodity capacitated plant location problems with inventory and out-sourcing aspects.

Ambrosino and Scutellà (2005) addressed facility location, warehousing, transportation and inventory problems. Meixell and Gargeya (2005) reviewed global supply chain design decisions from a practical point of view. 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. Integrated facility location problems addressing distribution costs, and inventory management for multiple products and multiple time periods was addressed by Gen and Syarif (2005).

Fleischmann, Ferber and Henrich (2006) developed a strategic-planning model for BMW to optimize the allocation of products to global production sites over a finite planning horizon. Melo, Nickel, and Saldanha-da-Gama (2006) proposed an integrated supply chain network model that include dynamic planning horizon addressing inventory, distribution, facility configuration, capital availability and storage limitations. Vila, Martel and Beauregard (2006) presented a mathematical model related to potential production-distribution facility locations and capacity options. Melo, Nickel and Saldanha (2009) mentioned that supply chain management literature mainly studied the facility location problems in automotive, food, chemical, forestry industries. We refer the reader to Shapiro (2006), Shen (2007) and Simchi-Levi, Kaminsky and Simchi-Levi (2009) for a comprehensive review of supply chain modeling and strategies.

To the best of our knowledge, energy infrastructure design is not studied in the supply chain management literature. In this paper, we extended supply chain management literature to the energy sector by developing a new class of location models to incorporate the unique features of energy supply chains.

2.2.2 Energy Economics and Policy

Energy economics and policy literature studies three related areas: (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. 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.

The 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 energy economics 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 papers study individual parts of the energy supply chain (power plants, coal transportation and power transmission) but don't consider an integrated energy supply chain from coal mining to power consumption. 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 end-to-end energy supply chain from coal mining to power consumption by supply chain management principles and mathematical programming models. For the first time, our model captures the interaction among different parts of an energy supply chain, such as the trade-off between coal-transportation related costs (inbound) and transmission-yield induced costs (outbound), in deciding power plant locations. Also for the first time, the model seizes the dynamic nature of limited reserves, increasing energy gaps and the interaction among energy, economy and budget. For the energy crisis of Pakistan, the model provides novel solutions that significantly outperform the government's plan and shed new insights on energy supply chain design.

Chapter 3

Coal-Fired Energy Supply Chain

3.1 Modeling Framework and Assumptions

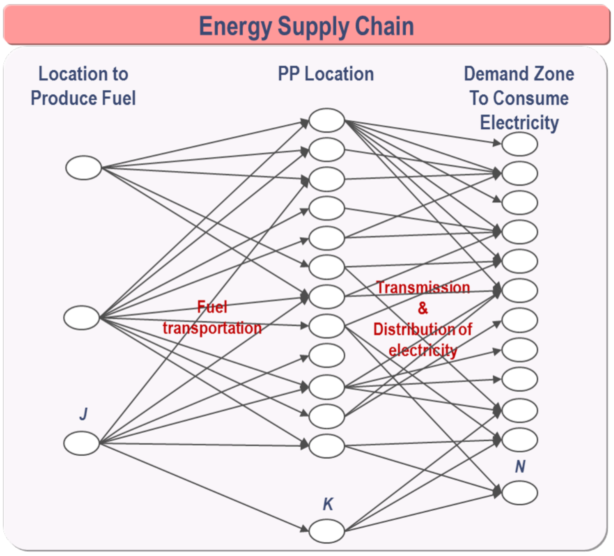


Figure 3.1: Network flow of energy supply

In Chapter 2, an energy supply chain is described that it includes various types of fuel, transportation method, power plant & its capacity, and transmission & distribution systems. (Figure 2.1) In addition, the same type of fuel can be produced at different locations, and various types of fuel can be produced together at the same location. (Figure 3.1)

Observation 1. *Observation on the Energy Supply Chain:*

1. *Various types of resources such as oil, gas, coal, and renewable resources.*
2. *Reserves (gas, coal, or oil) may run out.*
3. *For renewable resources, capacity may be limited.*
4. *The same type of resource may be produced at different locations.*
5. *Capital cost of fuel production is different at each site.*
6. *Operating costs of fuel production including labor fee, and other all variable costs depend on the amount of fuel produced.*
7. *Every type of fuel is transported from a single fuel location to multiple power plant locations, and a power plant sources the same type of fuel from multiple fuel locations.*
8. *Fuel is transferred via multiple types of transportation modes such as railway system, trucks, vessels, or pipelines.*
9. *Fuel production locations can have power plant locations.*
10. *If fuel production location, which has ample amount of fuel in a given period, is chosen, and if power plants is located at the same location, then power plants must source fuel locally, or may not source fuel from other fuel production locations. On the other hand, any fuel production location is limited (it may run out) is chosen and if power plants locate at the same location, then those power plants may source fuel from multiple reserves.*
11. *Power plants can be built either fuel reserves or demand zones.*
12. *Electricity is generated by power plants that may have different capacities.*
13. *Power plants are operated at full capacity.*
14. *At each of potential power plant location, a limit on the number of power plants that can be built given.*
15. *For building and operating power plants, both capital and operating costs are considered.*

16. *Power plant operating cost is yearly based, and is measured in terms of % of capital cost.*

17. *Electricity is transmitted from a single power plant to multiple demand zones, and a single demand zone sources electricity from either multiple power plants or multiple power plant locations.*

18. *Transportation route setup cost is given as a parameter that depends on the amount of fuel and distance.*

19. *Two types of transmission technology are tested up: HVAC (High Voltage Alternating Current), and HVDC (High Voltage Direct Current).*

20. *Building new transmission network and upgrading of existing transmission network are both required.*

21. *HVAC requires the upgrade of existing line and the setup of new grid stations.*

22. *HVDC requires the setup of new transmission line and to setup new converter stations for both converting AC to DC and inverting DC to AC back.*

23. *For HVAC existing lines are used, and grid station setup costs are dependent on PP location, given as parameters.*

24. *For HVDC new lines are built, and the costs of converting & inverting station are dependent on both distance and the amount of electricity transmitted.*

25. *No variable costs for operating transmission lines and grid stations.*

26. *The yield loss of transmission lines is 4.5% per every 100 miles for HVAC.*

27. *The yield loss of transmission lines is 0.429% per every 100 miles for HVDC. Additionally 2% loss is occur when converting and inverting.*

28. *Demand increases at the same % in every year.*

29. *Generation mix is given in terms of %*

30. *Existing electricity production is subtract from total demand. Therefore a demand parameter is the extra energy need.*

Decision variables are defined as described below: (Table 3.1)

Variable	Type
Which Fuel production locations are to be opened?	Binary
How much fuel is to be shipped from fuel production locations to which Power Plant location	Continuous
How many power plants are to be built at Power Plant location	Integer
How much power is to be transmitted from PP locations to demand zone	Continuous

Table 3.1: Decision Variables

This research aims to minimize total budget invested over a given period. According to the location and functionality, each group of constraints is classified and explained by class, (Table 3.2), thus the following regular assumptions are described. (Assumption 1)

Class of Constraints	**Name of Class**
Limited reserves at locations of fuel production	Fuel constraints
Transporter and route capacity limits	Transport route constraints
Limited number of PPs at each of PP locations	PP constraints
A power plant's output can't exceed its corresponding input and its capacity	Network constraints
Supply must meet demand of electricity at demand zones	Demand constraints

Table 3.2: Classes of Constraints

Assumption 1. *Regularity assumptions:*

1. *The budget is unlimited.*
2. *Assume that all infrastructures can enter in service immediately after decided to be operated. (Static)*
3. *Demand should be fulfilled.*
4. *Consumption follows the proportion of generation mix.*
5. *Power sources run as BAU (Business As Usual).*

3.2 Mathematical Models

We introduce a static energy supply chain model. Indexes, parameters, and variables are setup or defined in advance.

Index	**Name**	**Set**
j	Locations to produce fuel	$\{1, 2, \dots, J\}$
l	Different types of fuel	$\{1, 2, \dots, L\}$
i	Different modes of transportation	$\{1, 2, \dots, I\}$
k	Power plant locations	$\{1, 2, \dots, K\}$
w	Installed capacities of power plants	$\{1, 2, \dots, W\}$
n	Demand zones	$\{1, 2, \dots, N\}$

Table 3.3: Index

Fuel Location:			
w_j^l $l \in L, j \in J$	If a fuel location j entering service with type l, then 1. Otherwise 0	Binary	N/A
q_{jk}^l $j \in J, k \in K, l \in L$	Quantity of fuel shipped from j to k	Continuous	$: ton, etc$
b^{FL1}	Budget to setup fuel locations	Continuous	$: \$1,000$
b^{FL2}	Budget to operate fuel locations	Continuous	$: \$1,000$
Route:			
x_{jk}^{il} $i \in I, j \in J,$ $k \in K, l \in L$	If route between j and k entering service, then 1. Otherwise 0	Binary	N/A
b^{R1}	Budget for route setup	Continuous	$: \$1,000$
b^{R2}	Budget for route operation	Continuous	$: \$1,000$
b^{TR}	Budget for purchasing transporters	Continuous	$: \$1,000$
nt_{jk}^{il} $i \in I, j \in J,$ $k \in K, l \in L$	Number of transporters i newly operated between j and k.	Integer	N/A
z_{jk}^l $j \in J, k \in K, l \in L$	If pipeline between j and k entering service, then 1. Otherwise 0	Binary	N/A
Power Plant / Transmission Line:			
y_k^{lw} $k \in K, l \in L, w \in W$	Number of w MWh PPs using l type of fuel, which newly enetering service at PP location k	Integer	N/A
e_k^{lw} $k \in K, l \in L, w \in W$	Amount of electricity generated at k using l type of fuel with w capacity	Continuous	$: MWh$
p_{kn}^l $k \in K, n \in N$	Amount of electricity supplied from PP location k to demand zone n	Continuous	$: MWh$
b^{PP1}	Budget invested for building PPs	Continuous	$: \$1,000$
b^{PP2}	Budget invested for operating PPs	Continuous	$: \$1,000$
b^{TL}	Budget invested for building transmission lines and grid stations	Continuous	$: \$1,000$

Table 3.4: Variables: A base model

Fuel Location:		
FR^l_j $j \in J, l \in L$	Reserves of fuel type l at a location j	$: ton, m^3, barrel$
FS^l_j $j \in J, l \in L$	Capital cost of fuel type l at a location j	$: \$1,000$
FO^l $l \in L$	Unit operation cost of fuel type l at reserves	$: \$1,000$
Route/Transport:		
SB^i $i \in I$	Safety buffer between transporters.	minutes
TF^{il}_{jk} $i \in I, j \in J,$ $k \in k, l \in L$	Capacity of a transporter	$: ton, m^3, barrel$
PF^l_{jk} $j \in J, k \in k, l \in L$	Capacity of pipeline	$: ton, m^3, barrel$
RS^{il}_{jk} $i \in I, j \in J,$ $k \in K, l \in L$	Setup cost of route b/t j and k	$: \$1,000$
PS^l_{jk} $j \in J, k \in K, l \in L$	Setup cost of pipeline b/t j and k	$: \$1,000$
RO^{il}_{jk} $i \in I, l \in L$	Unit shipping cost	$: \$1,000$
TP^{il} $i \in I, l \in L$	Unit Purchasing cost of transporter	$: \$1,000$
Power Plant:		
CR^{lw} $l \in L, w \in W$	Conversion ratio from fuel to power	fuel / MWh
LP^l_k $k \in K, l \in L$	Limitation of PPs at PP location k	For $k \in \mathcal{K}_{\rangle}$
SC^{lw}_k $k \in K, l \in L, w \in W$	Setup cost of w MWh power plant to use l type of fuel at k	$ 1,000 per PP $: \$1,000$
PC^w $w \in W$	Capacity of power plant with w MWh	MWh
OC^{lw}_k $l \in L, w \in W$	Annual operation cost	$: \$1,000$ Unit:$1,000$
Transmission:		
SC^{TL}_k $k \in K$	Upgrading and connecting to existing transmission system at location k	$: \$1,000$
YL	Yield loss of HVAC line	$4.5\% per 100 miles$
Miscellaneous:		
G_n $n \in N$	Energy gap at demand zone n	$: MWh$
GM^l $l \in L$	Generation Mix from each type of fuel	%
D_{jk} $j \in J, k \in K$	Distance between fuel location and PP	$: 100 miles$
D_{kn} $k \in K, n \in N$	Distance between PP and demand zone	$: 100 miles$
M	Big number	2,000,000,000

Table 3.5: Parameters: A base model

Parameters describe set-up and operations costs for producing and transporting fuel, generating and transmitting electricity. Capacity of transporter, demands, distances between each locations, and other information are also described. (Table 3.5)

With parameters and variables defined, minimizing costs including all of variable costs and fixed costs is the objective of a mathematical model. The total cost consists of various types of cost classified by location and functionality. (Table 3.6): *Minimize*

$$b^{FL1} + b^{FL2} + b^{R1} + b^{R2} + b^{TR} + b^{PP1} + b^{PP2} + b^{TL} \tag{3.1}$$

s.t.

Cost	**Name**
b^{FL1}	Fuel location setup cost
b^{FL2}	Fuel location operation cost
b^{R1}	Route setup costs
b^{R2}	Route operation costs
b^{TR}	Purchasing cost of transporters
b^{PP1}	Setup costs of power plants
b^{PP2}	Operation costs of power plants
b^{TL}	Setup costs of transmission lines and grid stations

Table 3.6: Objective function: Costs of energy supply chain model

$$\sum_{k \in K} q^l_{jk} \leq \mathbf{FR}^l_j \cdot w^l_j \qquad \text{for} \qquad \forall j \in J \quad \textit{and} \quad \forall l \in L, \tag{3.2}$$

Fuel can be transported from a fuel location j to power plant location k after a fuel location j is ready to produce fuel l. Total amount of fuel l supplied from j to PP locations k must be less than the reserves of fuel l at a fuel location j.

$$b^{FL1} = \sum_{j \in J} \sum_{l \in L} (\mathbf{FS}^l_j \cdot w^l_j) \tag{3.3}$$

$$b^{FL2} = \sum_{l \in L} \mathbf{FO}^l \cdot \sum_{j \in J} \sum_{k \in K} q^l_{jk} \tag{3.4}$$

Each fuel location has a different setup cost for each of fuel types, FS_j^l, and an unit operating cost, FO^l depends on the amount of fuel type l produced.

$$q_{jk}^l \leq \mathbf{FR}_j^l \cdot \sum_{i \in I}(x_{jk}^{il} + z_{jk}^l) \qquad \text{for} \quad \forall j \in J, \quad \forall k \in K \quad and \quad \forall l \in L, \tag{3.5}$$

Fuel type l can be transported to a PP location, k by transporter type i, if a route or a pipeline are entering in service between fuel location j and PP location k.

$$(x_{jk}^{il} + z_{jk}^l) \leq \mathbf{M} \cdot \sum_{w \in W} y_k^{lw} \qquad \text{for} \quad \forall j \in J, \quad \forall k \in K, \quad \forall i \in I \quad and \quad \forall l \in L, \tag{3.6}$$

To operate power plants built at PP location k, then a route using a transportation mode i or a pipeline must be connected to PP location k from j for fuel type l.

$$nt_{jk}^{il} \leq \mathbf{M} \cdot x_{jk}^{il} \qquad \text{for} \quad \forall j \in J, \quad \forall k \in K, \quad \forall i \in I \quad and \quad \forall l \in L, \tag{3.7}$$

Transporters are entering in service only if a route is in operation between j and k.

$$q_{jk}^l \leq (\sum_{i \in I} \mathbf{TF}_{jk}^{il} \cdot nt_{jk}^{il}) + (\mathbf{PF}_{jk}^l \cdot z_{jk}^l) \qquad \text{for} \quad \forall j \in J, \quad \forall k \in K \quad and \quad \forall l \in L, \tag{3.8}$$

Transporters have different capacity, $\mathbf{TF}_{jk}^{il}$ according to a different route between j and k. Total capacity of a route should be equal to or larger than the amount of fuel transported between these locations. And a pipeline is also considered with the capacity $\mathbf{PF}_{jk}^l$.

$$nt_{jk}^{il} \leq \mathbf{RT}_{jk}^{il} / \mathbf{SB}^i \quad \text{for} \quad \forall j \in J, \quad \forall k \in K, \quad \forall i \in I \quad and \quad \forall l \in L, \tag{3.9}$$

It assumes that a transporter departs from fuel location j at least every given minutes after a previous one departed. SB^i is a kind of safety buffer between transporters.

$$b^{R1} = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} (\mathbf{RS}^{il}_{jk} \cdot x^{il}_{jk}) + \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} (\mathbf{PS}^{l}_{jk} \cdot z^{l}_{jk}) \tag{3.10}$$

$$b^{R2} = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} (\mathbf{RO}^{il}_{jk} \cdot \mathbf{D}_{jk} \cdot q^{l}_{jk}) \tag{3.11}$$

Operating cost depends on distance and amount of fuel shipped via route. A fixed cost is given as a j by k matrix, $\mathbf{RS}^{il}_{jk}$.

$$b^{TR} = \sum_{i \in I} \sum_{l \in L} \mathbf{TP}^{il} \cdot \sum_{j \in J} \sum_{k \in K} nt^{il}_{jk} \tag{3.12}$$

$\mathbf{TP}^{il}$, is paid for purchasing a single transporter.

$$\sum_{w \in W} (\mathbf{CR}^{lw} \cdot e^{lw}_{k}) \leq \sum_{j \in J} q^{l}_{jk} \qquad \text{for} \quad \forall k \in K \quad and \quad \forall l \in L, \tag{3.13}$$

Fuel is converted to power with a conversion ration for different fuel type l.

$$e^{lw}_{k} \leq \mathbf{PC}^{w} \cdot y^{lw}_{k} \qquad \text{for} \quad \forall k \in K, \quad \forall l \in L \quad and \quad \forall w \in W, \tag{3.14}$$

Electricity generated at k from fuel l with the capacity w, e^{lw}_{k} is limited by the capacity of power plant.

$$\sum_{n=1}^{N} p^{l}_{kn} \leq \sum_{w=1}^{W} e^{lw}_{k} \qquad \text{for} \quad \forall k \in K \quad and \quad \forall l \in L, \tag{3.15}$$

The total amount of electricity supplied from a PP location, k, can't exceed the amount of electricity generated at PP location k.

$$\sum_{l \in L} \sum_{w \in W} y^{lw}_{k} \leq \mathbf{LP}_{k} \qquad \text{for} \quad k \in \mathcal{K} \tag{3.16}$$

A set, $\mathcal{K}$, consists of subsets with different PP limitation. Each location has different limitation because of environmental and security issues. For mine reserve areas, there is no limitation to build power plants.

$$b^{PP1} = \sum_{l \in L} \sum_{w \in W} \sum_{k \in K} (\mathbf{SC}_k^{lw} \cdot y_k^{lw}) \tag{3.17}$$

$$b^{PP2} = \sum_{l \in L} \sum_{w \in W} \sum_{k \in K} (\mathbf{OC}_k^{lw} \cdot y_k^{lw}) \tag{3.18}$$

$\mathbf{SC}_k^{lw}$ is invested for building a single power plant with different capacity.

$$b^{TL} = \sum_{k=1}^{K} \mathbf{SC}_k^{TL} \cdot \sum_{l=1}^{L} \sum_{w=1}^{W} y_k^{lw} \tag{3.19}$$

No operating cost is applied in this model, and a parameter, $\mathbf{SC}_k^{TL}$ is a setup cost matrix of transmission lines and grid stations dependent on PP location k.

$$\mathbf{GM}^l \cdot \sum_{n=1}^{N} \mathbf{G}_n \leq \sum_{n=1}^{N} \sum_{k=1}^{K} \{(\mathbf{YL}^{\mathbf{D}_{kn}}) \cdot p_{kn}^l\} \qquad \text{for} \quad \forall l \in L. \tag{3.20}$$

Supply of electricity should be equal to or greater than its demand at demand zone n. It makes sure that the consumption of every demand zone meets supply of electricity. Yield loss is 4.5% (HVAC) In reality, a projected % of consumption comes from each type of fuel so that **GM** is given as %.

3.3 Numerical Study

In this section, the practical example of Pakistan is used. Especially, coal fired energy suply chain is addressed and we present what benefits come from it. Government plan is used the benchmark. Moreover, transmission types, HVAC and HVDC, are all considered.

3.3.1 Practical Example: Pakistan and its Government's Plan

We consider three coal mines such as the largest mine, *Thar*, the medium mine, *Sonda/Lakhra*, and the smallest mine, *Salt Range*. *Salt range* may run out, but other mines have eneough coal reserves. These mine locations also play a role as PP locations. And there are 24 demand zones including big and small cities that have different PP limitations respectively. Therefore 27 potential PP locations are considered. To ship coal from mine to PP location, trains are considered via railway, but we don't consider pipelines due to the large amount of water needes.

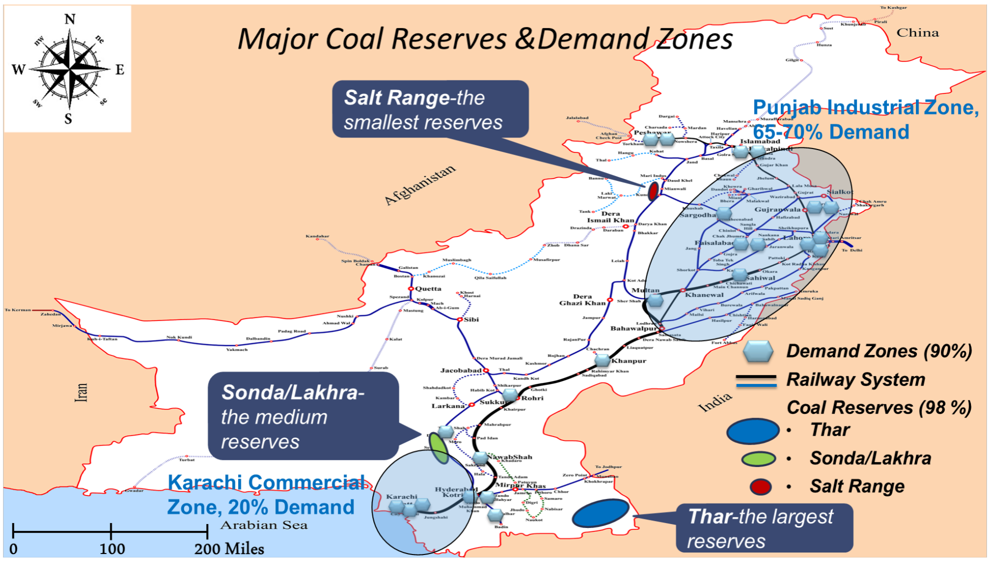


Figure 3.2: Major Coal Mines and Demand Zones

Based on basic assumptions discussed in chapter 3, we make additional assumptions for a coal based energy supply network of Pakistan.

Assumption 2. *Assumptions on the Coal-Fired Energy Supply Chain of Pakistan:*

1. *Three major coal mines, Thar, Sonda/Lakhra and Salt Range, are considered.(Figure 3.2) 98% of the country's total coal reserves come from these mines.*

2. *With Thar, Sonda/Lakhra, and Salt Range reserves, 50,000MWh can be harnessed for 500 years.*

3. *Salt Range may run out within 10 years for supplying 10,000MWh annually, but other mines can supply 10.000MWh for 7,251 years and 350 years respectively.*

4. *Mine operating cost is \$ 5.33 per ton, and it includes labor fee, and other variable costs related to the operation of mine.*

5. *At Thar and Sonda/Lakhra, if they are chosen for mining, then the power plants located at those locations must source coal locally. That is, no other mine can't supply coal to that mine being opened for mining. However, a PP location, Salt Range, cansource coal from other mines because it may run out.*

6. *Railway setup cost is given as a parameter. Railway operating cost is \$ 0.04 per mile per ton.*

7. *Power plants can be built at all of mines and at any demand zone. Thus 27 potential locations totally exist.*

8. *Power plants used in this model are either 300MWh or 500MWh capacity.*

9. *Power plant is assumed to be operated at full capacity with a daily consumption of coal at 2000 tons for 300MWh and 3,300 tons for 500 MWh.*

10. *Maximal number of power plants that can be built at each of PP locations is subject to some constraints such as environmental issue, accessibility and etc.*

    Thar, Sonda/Lakhra, and Salt Range: Unlimited.

    Small cities such that Khanpur, Badin, and etc: $\leq$ *10 power plants.*

    Other cities such that Karachi, Lahore, and etc: $\leq$ *5 power plants.*

11. *Build a power plant costs \$ 1 billion and \$ 2 billion for 300 MWh capacity and 500 MWh capacity respectively.*

12. *2% of power plant setup cost is spent for operating any single power plant annually. \$ 20 million and \$ 40 million are required for 300 MWh capacity and 500 MWh capacity respectively.*

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

14. *Transmission and grid station setup costs are dependant on PP location, and they are given as a parameter.*

15. *90% of the country's total energy supply are consumed by 24 demand zones (Figure 3.2).*

16. *20% and 60% of total consumption are asking for Punjob and Karachi respectively.*

17. *14 big cities are major energy-consumption cities and 10 of them are smaller cities but ideal locations for power plants.*

18. *40% of total consumption comes from coal. It's the global averge of energy mix.*

19. *Demand growth are increasing by 7% per year, and it's also assumed that no sudden variability of demand exists.*

20. *Models consider demand in the point of view of static aspect.*

21. *Thar, or Sonda/Lakhra mines meet a total electricity demand only if any mine is solely used. However Salt Range mine runs out.*

22. At demand zone, electricity generated or supplied from new power plants are only considered. The generation and supply of electricity from the system that has been already operated are not considered in this model. A demand parameter is an extra energy need that subtract power already in the system from total demand.

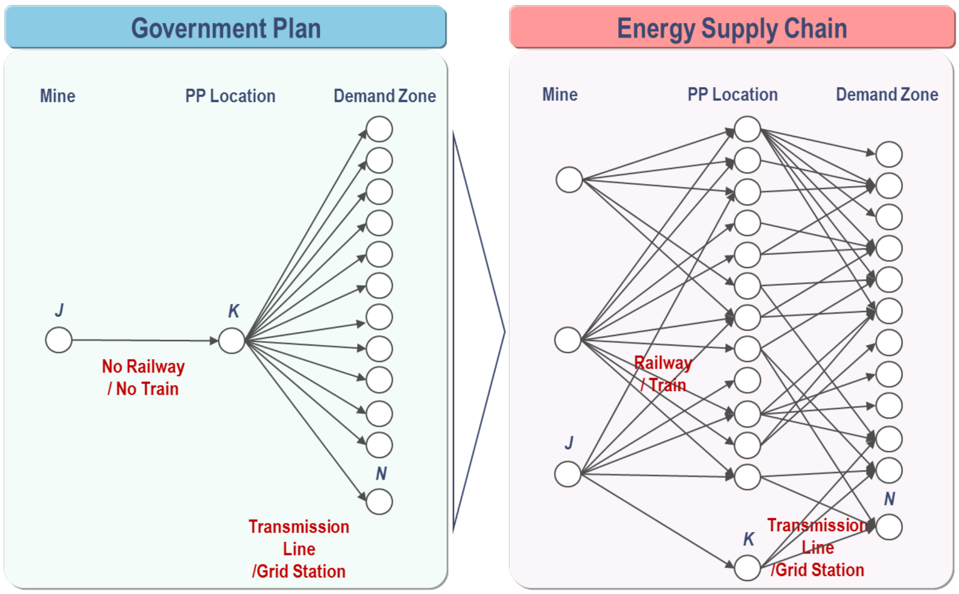


Figure 3.3: Coal-based Energy Supply Network: Single mine, single PP location, & 24 Demand zone (Left), 3 mines, 27 PP locations, & 24 demand zones (Right)

Government plan considers single mine, *That* to open for producing coal. and all of power plants is planned to be built at the same location. From this location, electricity spreads out cross the country. Thus it has single mine and single PP location, but 24 demand zones. we compare it with our model. (Figure 3.3)

3.3.2 The Effect of Energy Supply Chain Model

We demonstrate how an optimal solution outperforms government plan with various metrics. Coal efficiency and unit cost per MWh consumed are indicated.(Figure 3.4) For both plans, they supply enough electricity to all of demand zones. In addition, it always makes sure to use the minimum buget in energy sector. Let's discuss new findings in the results of optimal solution.

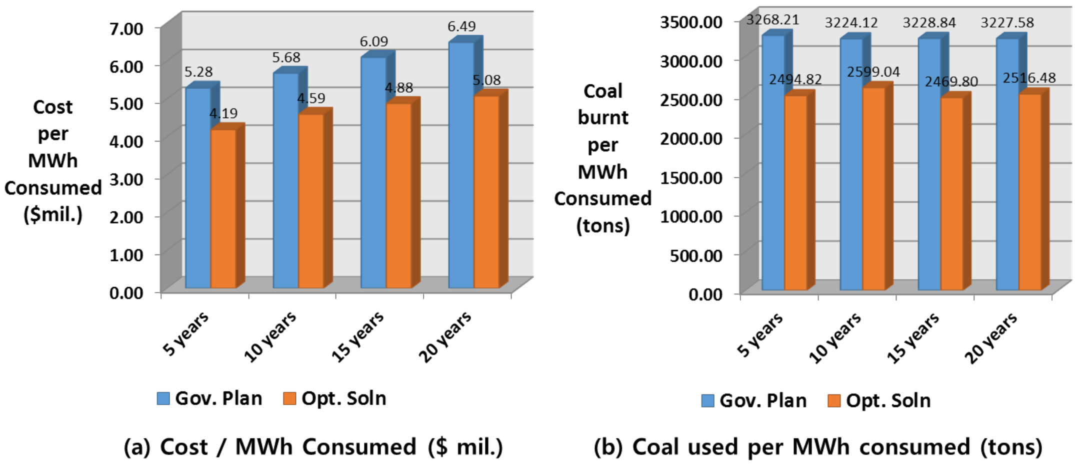


Figure 3.4: Gov. Plan v.s. Opt. Soln: Cost per MWh consumed & Coal burnt per MWh consumed

(b) of Figure 3.4 shows how much coal is burnt per MWh comsumed. It proves that opt. solution is more environment friendly, which is approximately 69% to 83% compared to government plan. We examine this ratio to explain why optimal PP location and mine location problems do matter for optimally designing and managing energy supply chain. Government plan spends much more coal than the optimal plan because all of power plants are built at a single location, *Thar* and it transmits electricity from *Thar* to everywhere. It means that much more yield loss exists in energy supply chain. Much more power plants must be built and much more coal must be transported and burnt. Therefore government plan spends higher budget in energy sector. ((a) of Figure 3.4) And government plan opens the most expensive mine ($ 6 bil.) compare to other mines ($ 2 bil. & $ 500 mil.). Ours results in cost saving and greenhouse gas emission.

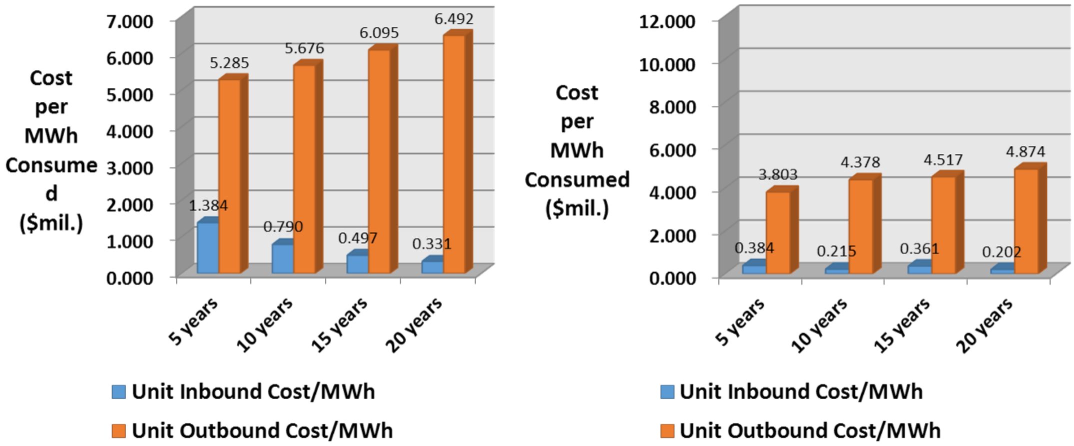


Figure 3.5: Gov. Plan v.s. Opt. Soln: In/Outbound Costs

Total costs increases sharply in time horizon. (Figure 3.6) It's explained with a projected demand. It assumes that demand grows by 7% annually. As compared to inboud cost related to coal transportation, outbound cost takes approximately greater than 90% of total investment in both of plans. (Figure 3.5). It clearly show that PP location is the most critical issue in energy supply chain. An optimal solution uses less cost compared to government plan. (Figure 3.6) Since both models assume that demand meet fully supply, we can assume that the same GDP growth is realized. however, an optimal solution shows that it has more net GDP due to less investment in energy sector. ((b) of Figure 3.6) As expected from total cost comaprison, larger number of power plants is asked to be built in government plan. Although two types of power plants are possible, it merely built power plants of 500MWh because it costs doubly. (Figure 3.7)

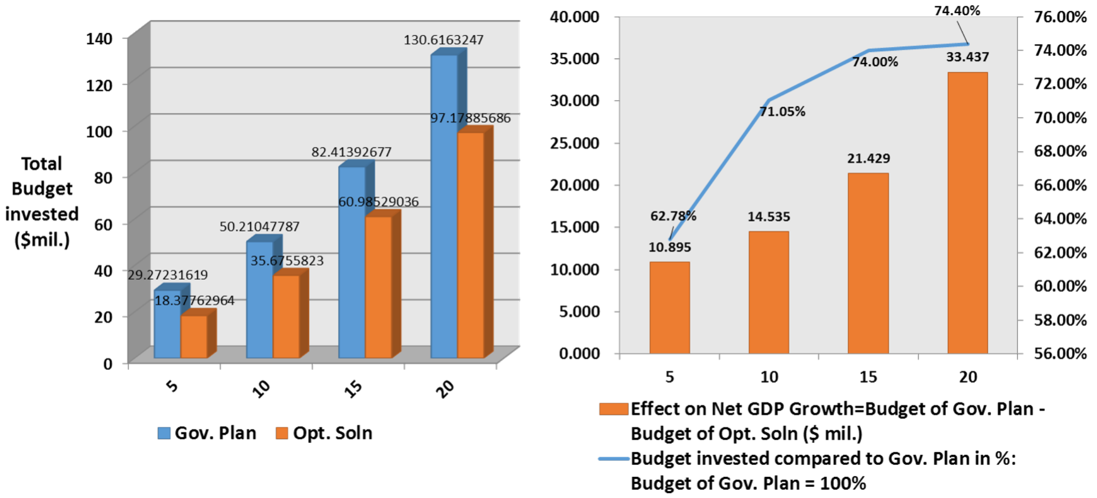
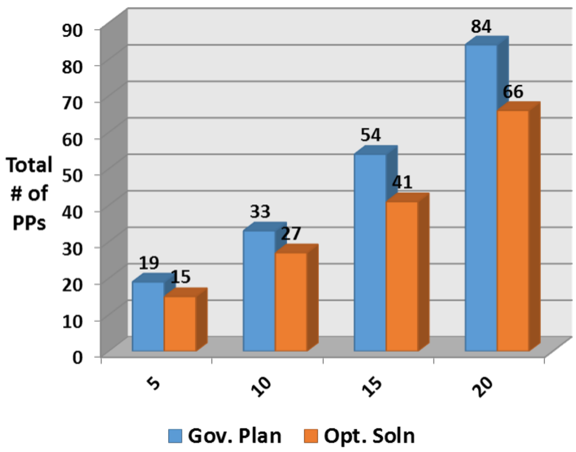


Figure 3.6: Gov. Plan v.s. Opt. Soln: Total Costs and Effect on Net GDP



Gov. Plan

# of PPs	5 years	10 years	15 years	20 years
300 MWh	18	31	52	83
500 MWh	1	2	2	1

Opt. Soln

# of PPs	5 years	10 years	15 years	20 years
300 MWh	15	26	39	66
500 MWh	0	1	2	0

Figure 3.7: Gov. Plan v.s. Opt. Soln: Power Plants built (300MWh & 500MWh)

Let's see the distribution of power plants and electricity across the country. An optimal solution opens *Salt Range* mine only because it's the least expensive. And it is the closest from the largest demand zone so that it does have higher impact on a supply of electricity.

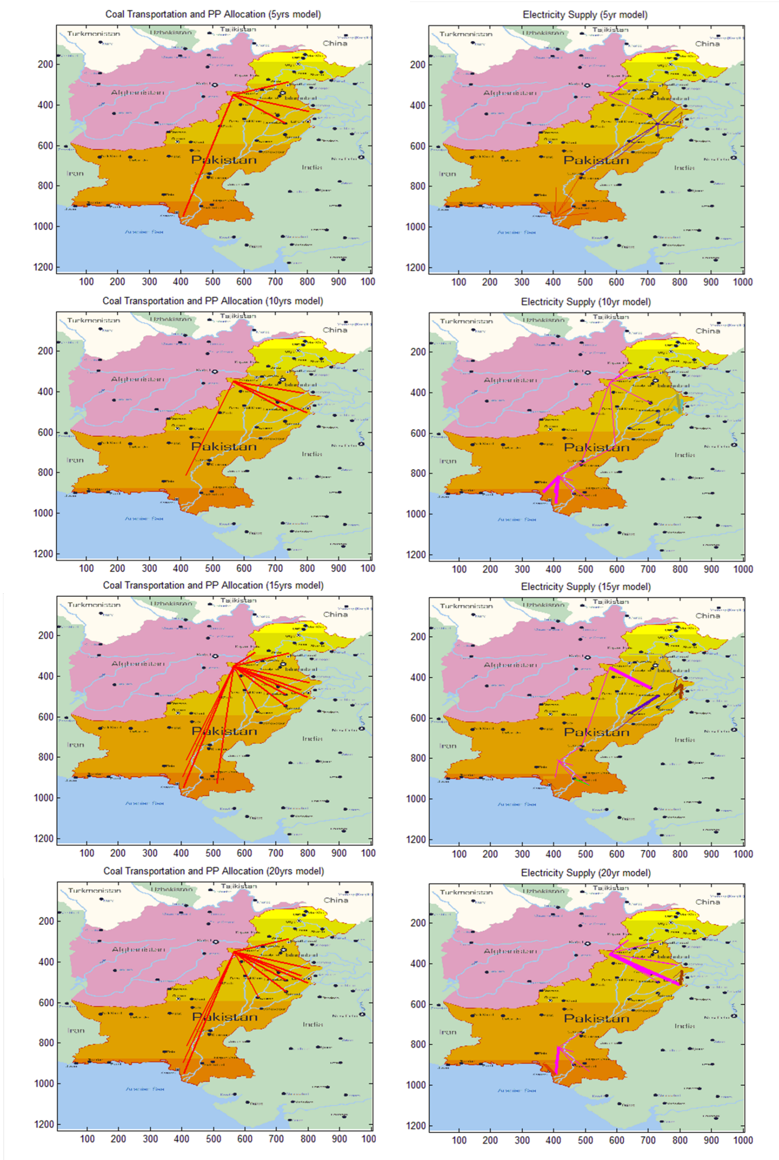
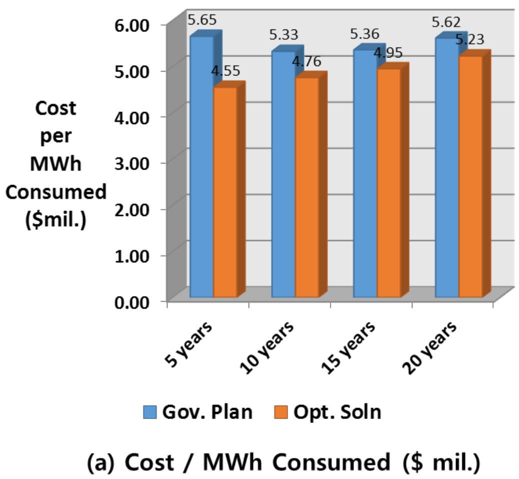


Figure 3.8: Action Plan (Continuous Model): Coal Supply and PP location & Electricity Transmission: 5 years, 10 years, ..., and 20 years

It supplies Coal to PP locations near two major demand zones for the period of 5years, and it expands a supply of coal to other PP locations. For a supply of electricity, it shows that northern and southern areas source power locally near demand zones or near two PP locations such as *Sonda Lagkra* or *Salt Range* closely located from major demand zones respectively. (Figure 3.8)

We also try to demonstrate benefits of different transmission system, which is here defined as a HVDC (High Voltage Direct Current). A mathematical formulation is slightly different from a HVAC model because HVDC transmission system has lower yield loss, but higher setup cost for building transmission stations. (Appexdix)

This energy supply model with HVDC transmission system opens /it Salt Range only. An optimal soltion shows similiar results in cost and coal efficiency with HVAC system such as an optimal solution work better than a government plan. (Figure 3.9)



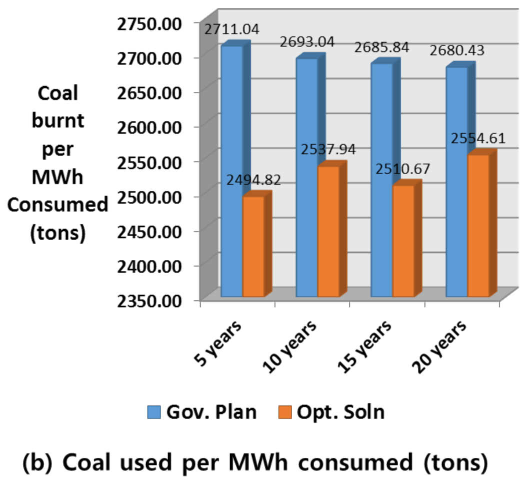


Figure 3.9: (HVDC) Gov. Plan v.s. Opt. Soln: Cost per MWh consumed & Coal burnt per MWh consumed

For government plan, HVDC reduces costs and an usage of coal due to lower yield loss. However, it doesn't make better outpur for an optimal solution compared to HVAC system because HVDC need much more cost for building stations up to convert AC to DC and invert DC to AC. HVAC system uses existing transmission system so that it is needed to upgrade only, but HVDC system must build new lines that HVAC does not require. And HVDC must build stations that costs more than HVAC. HVAC system only need sub-stations that push power up to demand zones. It also explain that PP location and mine location matter for designing an energy supply chain. (Figure 3.10)

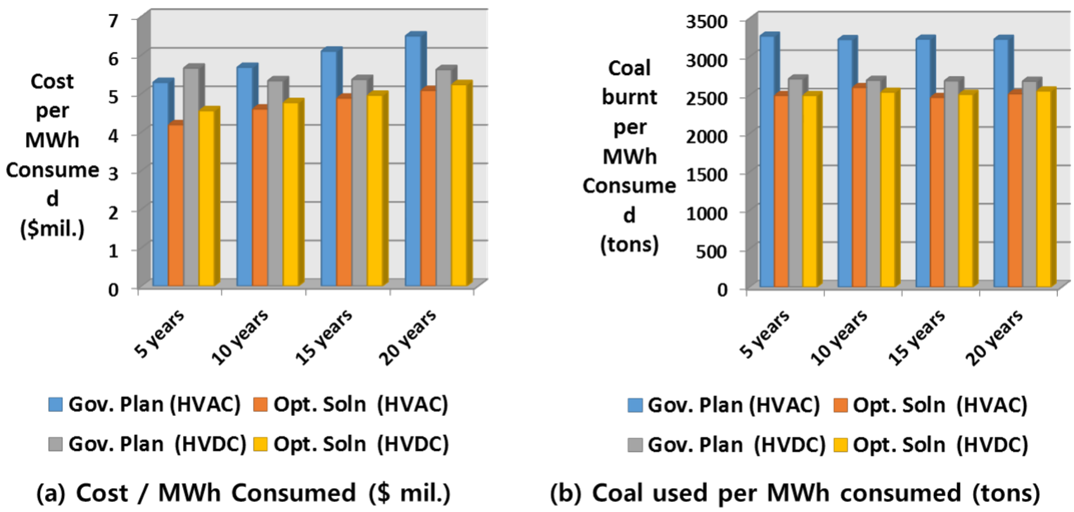


Figure 3.10: Comparision between HVAC and HVDC: Cost per MWh consumed & Coal burnt per MWh consumed

In HVDC system, outbound costs takes the most in total cost as well. And a decreasing trend of cumulated inbound describes that infrastructures are built at the beginning so that it has spent less cost over time as a supply of energy increases.

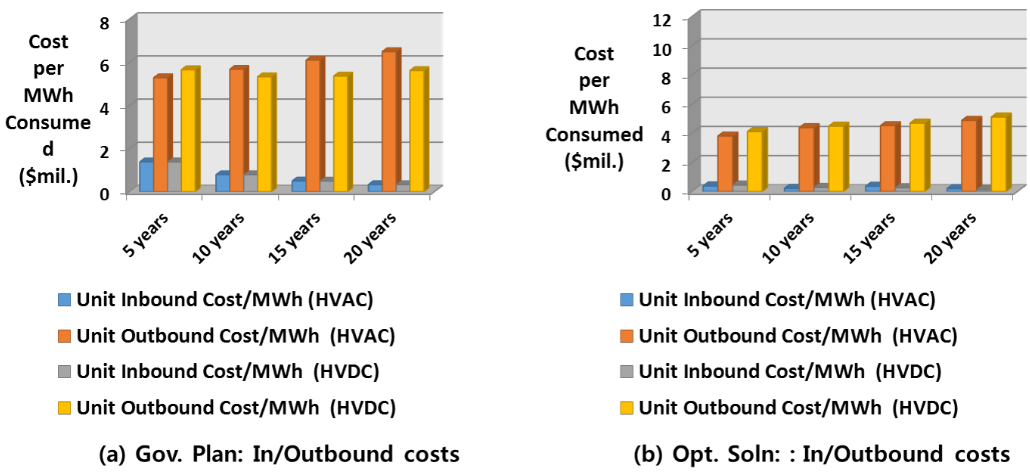
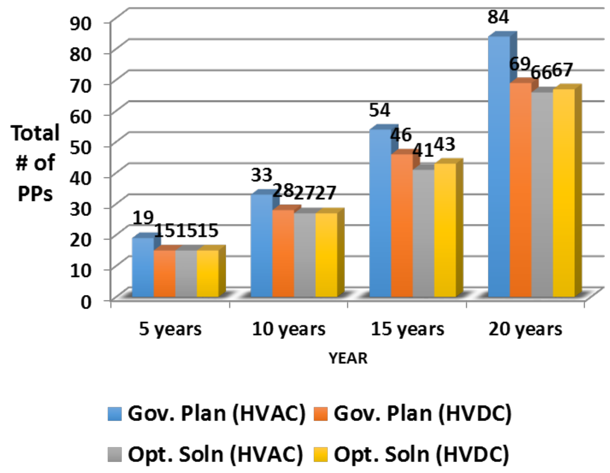


Figure 3.11: Comparision between HVAC and HVDC: In/Outbound Costs

HVDC costs less in a government plan, but it doesn't reduce cost in an optimal solution due to higher cost of converting stations. Moreover, PP location and mine location already affect on cost reduction in an optimal solution. (Figure 3.11)



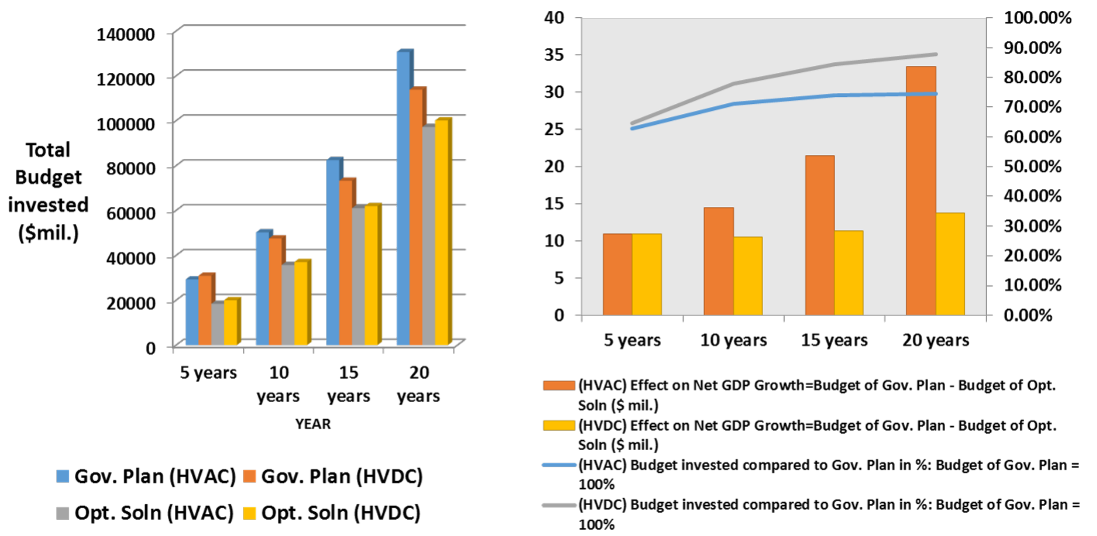
Gov. Plan

# of PPs	5 years	10 years	15 years	20 years
300 MWh (HVAC)	18	31	52	83
300 MWh (HVDC)	13	27	46	67
500 MWh (HVAC)	1	2	2	1
500 MWh (HVDC)	2	1	0	2

Opt. Soln

# of PPs	5 years	10 years	15 years	20 years
300 MWh (HVAC)	15	26	39	66
300 MWh (HVDC)	15	27	43	67
500 MWh (HVAC)	0	1	2	0
500 MWh (HVDC)	0	0	0	0

Figure 3.12: Comparision between HVAC and HVDC: Power Plants built



(a) Total Cost invested in energy sector ($mil.) **(b) Effect on Net GDP Growth in % & $ bil.**

Figure 3.13: (Comparision between HVAC and HVDC: Costs and Effect on Net GDP)

The thing to remember about what government plan is doing is that it can be really expensive. (Figure 3.12). 18 more power plants are required in HVAC. Even HVDC is used, it requires more power plants since it consider neither PP location nor mine location.

As it was assumed in HVAC model, enery consumption is the same for both government plan and optimal solution. Therefore an impact on net GDP is addressed and two different transmission systems are compared.When HVAC is applied, it makes out an optimal plan wealthier since HVDC system doesn't make a big gap between two plans. (Figure 3.13)

3.4 Summary

Countries in Africa, Asia, and other regions are more likely to suffer from energy poverty than enjoy economic prosperity. Like Gov plan of Pakistan, they try to make economy wealthier than before. But what does it mean for most of people who still live in energy poverty? It could not be realized with very limited budget. It doesn't have to be this way. Extreme energy poverty is far from being eliminated. Their story could be so different so that we focused turns from energy poverty to prosperity (security) as energy deficit ebbs in these countries, and our model tries to strategically integrates all of players such as fuel location, power plants, and demand zones for fully utilizing it at lower cost.

Our study suggests that it's the optimal solutions edge over any existing plan: strategically utilizes all of possible resources and infrastructure. Results of example of Pakistan show that an optimal solution can outperform government plan because it can establish a difference that it can preserve SCM principles. Our study also addresses an application of every existing transmission system so that it can be a good tool for designing an energy supply chain in practice. It delvers greater value to demand zones and establishes comparable value at a lower cost. The calculation of greater profitability is then realized; greater efficiency results in lower Investment budget. Finally economic growth will reawaken soon in those countries.

Chapter 4

Designing Energy and Water Supply Chains

4.1 Introduction

"As the world charts a more sustainable future, the crucial interplay among water, food and energy is one of the most formidable challenges we face. Without water there is no dignity and no escape from poverty." United Nations Secretary-General Ban Ki-moon on his message for World Water Day 2011.

4.1.1 The Water, Food, Energy and Flood Nexus

Water is a blessing; it is not only an indispensible element of human life but also brings about many economic benefits, such as food and energy. However, achieving water, energy and food security for all is still one of the greatest challenges facing humankind.

As of today, nearly one billion people lack access to safe drinking water, one billion people suffer from hunger and 2.5 billion people do not have access to electricity (FAO 2014, IEA 2006).

Geographically, energy deficient regions are highly correlated with those facing food shortage and economic water scarcity. South and east Asia and Sub-Saharan Africa are the regions in the world with the lowest electricity consumption per capita. For instance, the electricity consumption per capita is 480.5 kWh in India, 460 kWh in Pakistan, and 36.3 kWh in Ethiopia, far below the world's average of 2596 kWh (IEA 2014). Su-Saharan Africa, in particular, has two thirds of its population, about 585 million people, no access to electricity (IEA, 2011). The same regions also suffer severe malnutrition and economic water scarcity. For instance, more than half of the sub-Saharan African countries have 25% or more of their population undernourished; water resources are abundant relative to that withdrawn for human benefits (Earthscan 2011).

The situation can get worse in the future as population growth and economic development accelerate demand for food, water and energy. As predicted by UNDESA (2009), the world population is expected to grow from 6.9 billion in 2010 to 9.1 billion in 2050. By 2050, global demand for food is predicted to increase by 60-70% (Bruinsma 2009, FAO 2009), demand for energy and water will increase by 80% and 55% respectively (OECD Environmental Outlook 2014).

Water is also a curse because flood is the top killer among all natural disasters. Globally, floods accounted for 31% of all natural disasters that occurred in the 20th century (Guha-Sapir et al. 2012), but 84% of all disaster-related deaths between 2000 and 2005, and 65% of disaster-related economic losses between 1992 and 2001 (ADB 2009). Asia is the continent suffering the most from flood - during 1900-2012, flood disasters in Asia (40% of worlds total) resulted in 6.8 million deaths (98% of deaths worldwide), displaced 3.4 billion persons (95% of affected persons worldwide), and caused $330 billion (60% of worlds total) in economic losses (Sodhi, Tang 2014).

As advocated by Food and Agriculture Organization (FAO) of the United Nations in 2014, the issues of water, food, energy and flood are highly interconnected in the context of sustainable development of economy and society for developing countries. For instance, increasing agricultural output will substantially increase water consumption because agriculture accounts for 70% of the global freshwater withdrawal (FAO 2014). Seasonal fluctuations in precipitation cause floods and droughts alternatively. Running water in rivers can generate energy and hydropower presents the largest renewable source of electricity generation. Finally, the economy and public budget for infrastructure development of developing countries depends heavily on their energy consumption and agriculture output but are negatively affected by the severe issues of flood.

4.1.2 Hydropower Development - A Priority

The development of hydropower has the potential of addressing the interconnected issues of water, food, energy and flood all in the same time. Thus, it plays a critical role in sustainable development and economic prosperity of many countries. Hydropower systems provide not only electricity but also many economic benefits such as flood control, irrigation and water supply, by enhancing security against fluctuations in the availability of water and thus benefiting users throughout the year.

Hydropower is the most common form of renewable energy (IEA 2011). It is clean and efficient with the best turbines having hydraulic efficiency in the range 80 to over 90% (Renewables First 2016). It is reliable and viable for massive energy production and also represents a flexible peak-load technology (IHA 2014). Economically, the generating cost of hydroelectricity is relatively low, making it a competitive source of renewable energy (Cheng, Shen, Wu, Chau 2012). Hydro reserves are widely available and the enabling technology is proven with relatively low technical requirement (e.g., relative to nuclear), thus they are accessible to and feasible for many developing countries. Currently, it provides a significant portion (15% in 2007) of the worlds total electricity supply and is used in over 150 countries (World Energy Council 2013).

It is estimated that two-thirds of the worlds economically feasible potential of hydropower is yet exploited (WEC, 2010). Developing countries, such as those in Africa, Asia and Latin America, have an especially high percentage of unexploited hydro resources. For example, 12% of the worlds hydropower potential is found in Africa, but only 5-10% of the potential is captured, in sharp contrast to the worlds average of 20% (van der Wat 2013). The lack of hydropower facilities in developing countries, not only leaves a majority of their population no access to electricity, but also provides no means for the government to handle the alternating issues of drought and flood. The result is that a large portion of the agricultural land cannot be irrigated, meanwhile severe floods occur frequently and cause significant damages and casualties.

The case of Pakistan is exemplary. Pakistan is suffering severe energy deficiencies in recent years despite its abundant hydropower resources. On one hand, the country has a 6,000 MWh shortfall out of 16,000 MWh total consumption in 2011, a nearly 40% deficit. On the other hand, Pakistan has rich hydro resources - the Indus river system runs across the entire country from the highest mountain in the world, the Himalayan in the north, to Arabic sea in the south within 1000 miles. However, only 11% of the collective hydropower potential is captured.

In addition to energy deficiency, Pakistan also suffers significant irrigation issues and severe flood damages. Pakistan is an agriculture country where more than 138 million people depend on irrigated agriculture for their livelihoods in the cultivated areas of about 14 million hectares in the flood plains of the Indus river (ADB 2013). However, only about 50% of all agricultural land in Pakistan is irrigated. Improving irrigation can significantly improve the economy and society of the country as agriculture contributes to about 25% of the GDP and 45% of employment. Flood is another major issue related to water resource develeopment due to the monsoon season - the seasonal variation of precipitation. In Pakistan, floods and rain account for nearly 91.4% in economic losses among all natural disasters. Between 1950 and 2011, there is a major flood almost every 3 years. On average, the annual flood damage from 1960 to 2011 was about 1% of the mean annual GDP (Luo, Maddocks, Iceland 2015).

Recognizing the potential of hydropower, the Beijing Declaration agreed at the United Nations Symposium on Hydropower and Sustainable Development in 2004 pledged “the developing countries and undeveloped countries to pay considerable attention and prioritize the development of hydropower for poverty reduction, achieving the Millennium

Development Goals, promoting the sustainable development of the economy and society and improving the environment."

Many governments in the developing world, including Pakistan, have prioritized hydropower projects. But significant challenges lie in the efficient exploitation and utilization of hydro-resources to meet the diverse needs of energy, food and flood control, especially under tight financial resources. In 2014, FAO called for studies on the nexus among water, food and energy; it also emphasized a systematic thinking to identify synergies and trade-offs among different development goals, and to conduct quantitative study to maximize the overall benefits in the long term by taking into account the dynamic nature of complex systems.

In response to the call of FAO 2014, we develop mathematical models in this paper to capture the nexus of water, food, energy and flood and provide solutions and insights to efficiently expand hydropower network under limited budgets to meet the diverse needs of energy, irrigation and flood control. The objective is to enhance energy and food supply, mitigate flood damages and achieve the overall economic prosperity for developing countries with abundant hydropower reserves.

4.1.3 Hydro Supply Chains

To capture the interconnected issues of water, food, energy and flood, we present the hydro supply chain concept to encompass the system-wide perspective from hydropower network on a river system to the distribution of water and power to various demand zones. Specifically, a hydro supply chain includes the river system, hydropower facilities, water and energy demand zones, their linkages to the hydropower facilities (transmission network, canal and pipe system), and flood zones (see Figure 4.1). Electricity is generated at hydropower plants and transmitted (distributed) via the transmission network to energy demand zones (e.g., cities, industrial and commercial hubs); water is withdrawn by the hydropower facilities and distributed via the canal and pipe systems to water demand zones (e.g., farmland, cities). Finally, excessive water may overflow from the river basin to nearby flood zones. We first note that the major energy demand zones may not overlap with the major water demand zones especially for developing countries whose economies rely heavily on agriculture. Second, both demand zones can be far away from the river basin, along which flood zones are typically located.

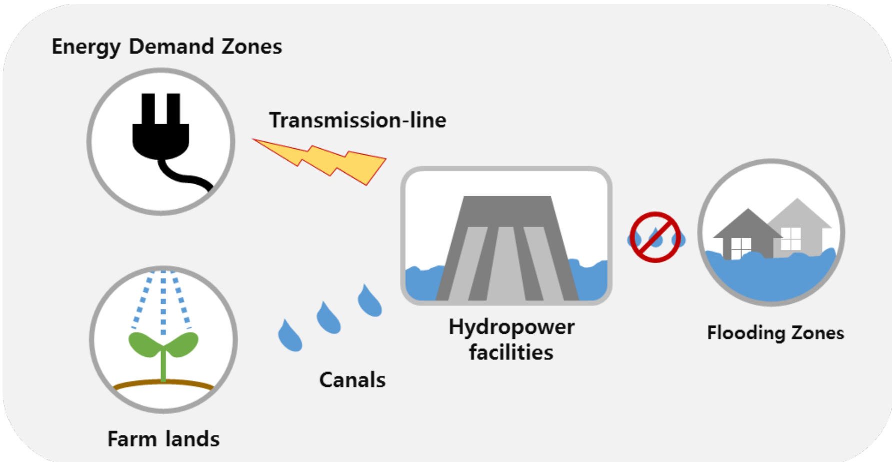


Figure 4.1: Hydro supply chain.

Despite many variations, there are essentially two types of hydropower facilities: a dam and a barrage. The key difference between them is the reservoir. A dam has a reservoir behind it from which water is taken to drive hydraulic turbines in the powerhouse. A barrage (also called run-of-river, or ROR) has no reservoir, instead it takes water directly from the river to the powerhouse where the turbines are installed. A dam can generate energy and store water, thus it provides a buffer against fluctuations in precipitation to ensure more stable water supply and better flood control. A barrage, on the other hand, can generate energy but cannot store water, thus it provides a limited or no flood control and its water supply varies by season. Dams are typically more expensive and take longer to build than barrages. The choices of the type and capacity (power and storage) are site dependent (Silva 1991).

A hydro supply chain in a developing country has the following features and economics:

1. The hydropower network should serve multiple needs including energy, irrigation and flood control coming from dispersed and non-overlapping zones. Water used for irrigation typically is not used for power generation, and vice versa.

2. Hydropower facilities with reservoirs (i.e., water storage capacities) can moderate the variation of water availability (e.g., precipitation) across seasons. Thus they serve multiple purposes such as water storage, irrigation and control flood.

3. Consecutive hydropower facilities on the same river system interact with each other as they divide up local precipitation and one's flow control decisions (withdraw, release, store) affect all others downstream.

4. Yield losses in power transmission (Kessides 2013) and water distribution (FAO 2016, Seckler 1998) cannot be ignored; evaporation loss on stored water must be considered (Mcjannet 2013).

5. Irrigation contributes to agriculture output; power consumption and agriculture

contribute to the economy; less flood reduces the economic losses.

These features, except the yield losses in power transmission and the dependence between energy and economy, are not shared by other power sources but unique to hydropower.

In this paper, we take the standpoint of governments (or their representing agencies) in developing hydropower because in developing countries, it is often the government who leads the development effort of basic infrastructure through public funds. In the case of Pakistan, the representing agency is its Water and Power Development Authorities (WAPDA). To design a hydro supply chain from a government perspective, we shall focus on strategic and tactic decisions such as hydropower location, portfolio (size, type), and sequence (or timing), distribution decisions of power and water from each facility to each demand zone, and water control decisions (withdraw, release, storage) at facilities over time.

4.1.4 Synergy, Trade-offs and Dynamics

To optimize hydro supply chains for developing countries with limited financial resources, we shall identify the synergies, trade-offs and dynamics in these interacting and dynamic systems with multiple development goals.

Interacting facilities, synergies and conflicts. Working together, the network of hydropower facilities can regulate seasonal precipitation and achieve the synergies between securing water supply for irrigation in the dry season and controlling flood in the raining season. To ensure that they work in harmony, however, we must consider their interaction. Specifically, hydropower facilities on the same river system can strongly interact with each other in a cascading way similar to multi-echelon inventory systems. That is, the inflow of a facility is proportional to the released outflow of its immediate upstream facilities plus local precipitation. Thus, more water stored or used at upstream reduces the flow to downstream. The interaction leads to conflicting requirements on hydropower network between flood prevention and irrigation. In the raining season, the facilities share the load in flood control, and so more facilities may be preferred. In the dry season, facilities may compete for water, and so fewer facilities may be preferred. The implication is that hydropower facilities shouldn't be planned in isolation of each other, but should be planned jointly and spaced out strategically to complement (rather than fight) each other and achieve the best overall performance.

The collective needs of irrigation and flood control are also inherently conflicting with that of power generation because more storage of water (more dams) can better serve the purpose of irrigation and flood control but incurs higher evaporation losses and leaves less water for power generation. Because barrages are typically cheaper to build than dams, thus they are preferred to dams if there is no need to store water. Thus these conflicting objectives essentially lead to the issue of mix between dams and barrages, that is, if power generation is more desirable than irrigation and flood control, then more dams (fewer barrages) should be built under the limited budget. In practice, we observe opposite strategies as some countries (e.g., Pakistan) build mostly barrages while others (Congo) just dams (Kermeliotis 2016).

The cost trade-offs. The design of hydro supply chain involves multiple cost trade-offs. First, we must balance the supply vs. demand best locations for hydropower.

Supply best locations (i.e., ideal locations from a supply perspective) are those with ideal geological conditions (e.g., in mountain areas), and thus having the lowest unit setup cost and largest installed capacity. Demand best locations (i.e., ideal locations from a demand perspective), on the other hand, are those close to geographically dispersed major demand zones and/or flood zones (e.g., in flood plains), and thus can meet the diverse needs at the lowest yield losses. Clearly, a supply best location may not be demand best (and vice versa) as it can be far away from the demand and flood zones; so their functions of energy and water supply and flood control are diminished via distance.

Second, the hydropower location must balance the needs of different sectors (development goals) because energy demand zones may not overlap with water demand zones and flood zones (see Figure 4.2 for an example of Pakistan). Thus the best hydropower location for energy may not be the best for irrigation and flood prevention. The cost trade-offs highlight the impact of distribution yield losses on hydropower locations and the challenge in selecting the few from the many potential sites with different cost and capacity.

Different ways to handle these cost trade-offs lead to different practices. For instance, the supply best locations drove the site selection decisions in many developing countries (Pakistan, Figure 4.2, Congo, Kermeliotis 2016) where a few sites with the largest capacity and lowest unit cost are picked. Doing so achieves the economics of scale in setting up the facilities but loses the location flexibility of the opposite strategy that builds many small sites (Kenya, Turkey - Yuksek, et al. 2006, and China in the 1950s, Lewis 2013) under the same budget. Or a hybrid strategy, e.g., the Brazilian and Chinese hydropower systems are composed of a few very large storage reservoirs and many medium- and small-sized hydropower plants (Barros, et al. 2003).

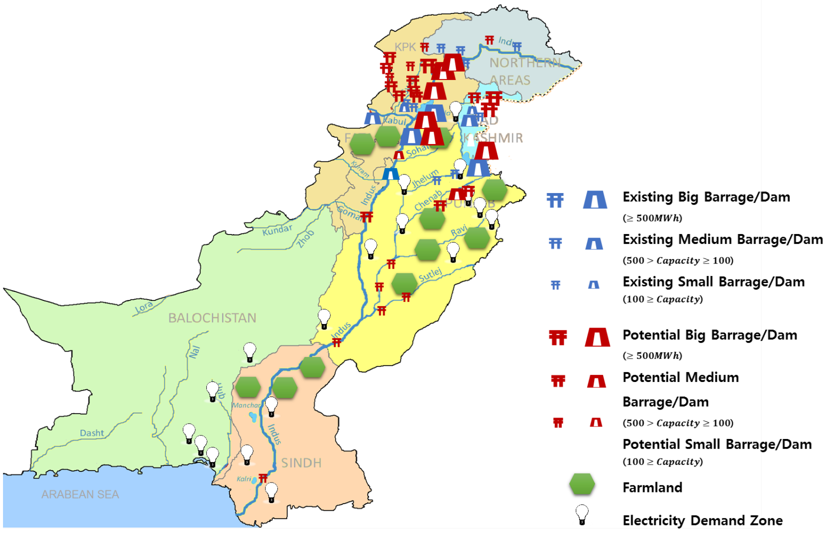


Figure 4.2: Pakistan map of existing and potential hydropower locations, demand and flood zones. Source: PPIB 2011.

Another pair of popular but opposite practices is the concentrated or dispersed hydropower locations. The supply best locations are highly concentrated in the mountain area (e.g., Pakistan, the far north part of the country, see Figure 4.2), but the demand locations may scatter across the entire country. Concentrating hydropower facilities in the supply best locations (Pakistan, Figure 2) achieve cost efficiency in facility construction but loses location flexibility of the dispersion strategy (e.g., China) to meet demand and prevent flood. This is true not only because the supply best locations can be far away from the demand and flood zones, but also because of the interaction among the hydropower facilities (e.g., competition for water) which may negatively affect their irrigation and flood control functions.

The time trade-off. Finally, the tight financial resources affect the ways in which developing countries expand their hydropower networks. The financial resources for infrastructure development of hydro resources often come from public funds that strongly depend on the economy, which, in turn, depends on energy consumption, irrigation and flood control. This water-economy cycle implies an important time trade-off, where fast influx of new energy and irrigation water, and quick resolution to flood issues can boost economy quickly which leads to more budget available for future development. Such a dynamic interaction among budget, development and economy cannot be ignored for these countries.

The time trade-off affects the sequence of site selection. Some developing countries (Pakistan, Congo) choose to build large sites first, while others built small site first (Kenya, China in 1950s'). Small sites tend to have higher unit costs but are quicker to build and faster to impact, while large sites may save construction cost unit-wise but take a longer time. Similar concerns apply to the sequence of building dams and barrages where barrages have fewer functions but are quicker to impact than dams. Regardless of the strategies, we must plan hydropower sites strategically over time by leaving space to build more in the future in order to maximize their synergies and avoid their conflicts.

4.1.5 Research Questions and Main Results

The synergy, trade-offs, and dynamics of hydro supply chains lead us to the following research questions: How to build up a hydropower network under limited financial resources to effectively meet the diverse needs of energy, irrigation and flood control from dispersed and non-overlapping demand zones? How does the limited financial resources and its resulting time trade-off shape up the best course of hydropower expansion decisions (location, mix and sequence) over time? Regarding the popular practices, we ask more specific questions: Given limited budgets, should we build a few large hydropower sites at concentrated supply best locations or many small sites and spread them out to dispersed demand best locations? How to locate the hydropower facilities to balance the yield losses between power and water distribution? What is the optimal mix of dams and barrages to serve the conflicting needs of power generation, water supply and flood control? Given a portfolio of sites with different capacities (large and small) and types (barrage and dam), what is the optimal sequence to build them?

In this paper, we take a supply chain management perspective of water resources development in developing countries and define the concept of "hydro supply chains" which encompasses an end-to-end view from interacting hydropower facilities to power and water distribution and to demand and flood zones. We mathematically model the nexus of water, food, energy and flood in hydro supply chains and present a new class of location optimization models to expand hydropower network under limited budget for energy security, irrigation and flood control. The model captures the unique features and economics of hydropower in developing countries such as heavy yield losses in water and power distribution, diverse needs of dispersed demand and flood zones, synergy and conflict among multiple development goals, and the dynamic interaction among water resource development, economy and budget.

Applying the model to the real life case of Pakistan, we generate solutions that can significantly outperform common practices in all dimensions of energy consumption, irrigation and flood control. Specifically, the solution first builds up many small hydro (dams and barrages) sites close to demand and flood zones to have a quick impact on the economy; with more funding available it then builds up large sites in more remote areas. In all scenarios, the hydrpower sites are spread out strategically to leave space for the others to be built in the future. The optimal solution follows a hybrid approach that first opens demand best sites then supply best sites; thus it differs from common practices which are driven either by supply best locations or by demand best locations. Our results demonstrate the value of the supply chain perspectives in hydropower network expansion by showing the impact of distribution decisions on the location of hydropower sites and how the water-economy cycle (time trade-off) shapes up the sequence of the sites. A sensitivity study is performed to test the robustness of the results and the impact of various system parameters. We also provide insights on the relative performance of popular but opposite practices for developing countries with limited financial resources.

The rest of this paper is organized as follows: In Section 4.2, we review the related literature, point out the unique features of the problems consider in this paper, and elaborate on our contributions. In Section 4.3, we present assumptions, justifications and the modeling framework, as well as models to capture facility interaction and nexus of flood, power and irrigation. In Section 4.4, we provide the mathematical formulation of the mix-integer programming (MIP) model. In Section 4.5, we apply the model to the real-life example of Pakistan to generate solutions and develop insights. Section 4.6 concludes this paper.

4.2 Literature Review

The development of hydropower network to address the nexus of water, food, energy and flood is a topic lying at the interfaces of water resources management and development, energy system planning, and operations research and management. We shall review closely related work in each area and point out the contribution of this work.

Water Resources Management. The control of water flow in multi-reservoir systems has been studied extensively in the water resource management literature. The decisions are centered around water storage, routing, usage and releasing subject to a variety of problem specific constraints, for purposes such as energy generation (Grygier and Stedinger 1985), flood control (Windsor 1973), and irrigation (Cai, et al 2002). Yeh (1985) and Wurbs (1993) provide reviews of this area with respect to the issues, models and optimization algorithms. More recent work also included water distribution, deliveries and movement among regions, please see Jenkins (2004) and Harou (2009). Cai, et al (2002) considers distribution efficiency in water resource management for irrigation. Hu, et al. (2015) describes an application to optimize the generation portfolio of a six-dam system in real time to meet the requirements of flood control and electricity reliability under uncertainty. However, this literature focuses on the optimal control and management of established water resources systems without network expansion and location decisions.

Capacity Expansion in Water Resource Systems. Capacity expansion planning of water resource systems determines future expansion in time, size and locations of assets to meet the increasing demand of a specific commodity. The early work in this literature focuses on sequencing capacity expansion projects for power and/or water demand without considering the spatial configuration of the system (e.g., Erlenkotter 1973). O'Laoghaire and Himmelblau (1971, 1972, 1974) study the expansion of hydropower network on a river system to optimize net irrigation and energy benefit subject to budget, demand, flow balancing and institutional constraints. The flow control issues are also considered in the network expansion models by other authors, such as Martin (1987) which separates the problem into capital investment and system operation subproblems, and solves them by network optimization models and a dynamic programming algorithm. Luss (1982) provides a thorough review of general capacity expansion models with applications in water resources development.

More recent work in this literature considers distribution decisions. For instance, Hsu, et al. (2008) provides a network flow model to optimize water distribution which helps to identify the bottlenecks. Based on the results, capacity expansion alternatives are proposed and evaluated iteratively. Beh, et al. (2014) studies the sequencing of water supply projects by incorporating alternative supply sources and multiple objectives, including cost and greenhouse gas (GHG) emissions. Padula (2015) provides a thorough review of the recent development in this literature.

Most work in this literature focuses on developed countries, from which developing or undeveloped countries have many distinct features.

1. The hydropower network is barely existent, government often takes the lead in the development through public funds.

2. The issues of energy, water (irrigation) and flood are interconnected and equally important for the economy and society.

3. Heavy yield losses in power and water distribution due to aging and poorly maintained infrastructure.

4. Limited financial resources which depend on economy, which, in turn, depends on the development of water resources systems.

Developed countries are quite on the contrary, where the system is well established and it is often the market and individual companies that drive the development while government plays an indirect role by designing policies. In developed countries, flood is often a lesser issue than energy and water supply and thus rarely considered together with the other two. Likewise, yield losses can be minor and many studies do not consider dispersed demand zones but just lump all demand together regardless of their locations. To our best knowledge, the yield losses of water and power is yet considered together in this literature. Finally, this literature either does not consider budget or consider exogenous budget.

Our work incorporates these unique features and contributes to this literature in the following ways: First, we expand the existing literature to include all three development goals, i.e., energy, water and flood, by mathematically modeling their nexus to capture their synergies and conflicts. Second, we provide the end-to-end perspective to this literature by including both power and water distribution decisions with distance-based yield losses in the hydropower network expansion decisions. Third, we consider endogenous budget that depends on the economy, which in turn, depends on effective development and utilization of the hydropower system to balance the conflicting goals of energy consumption, irrigation and flood control.

Energy system planning. The literature plans integrated energy systems with a portfolio of power generating technologies (including hydropower) at a strategic level for a country or a region. One most notable class of models, the MARKAL family models, aims at minimizing the total cost of providing energy to meet the demand of diverse industry sectors. The MARKAL-MACRO model further links energy system planning to macro-economics through supply-demand dynamics and energy cost. We refer the reader to Connolly, Lund, Mathiesen and Leahy (2010) for a thorough review. Models in this literature typically do not consider budget constraints except Kuby, et al. (1993) which provides a strategic planning model for China's thermal, hydro and nuclear power generations, fuel transportation, and electricity delivery under exogenous budgets.

Most work in this literature focuses on cost efficiency and environmental issues - important to developed countries, but it typically does not model the detailed interaction among hydropower facilities, and has yet considered energy, irrigation and flood control issues jointly important and interconnected issues in developing countries (FAO 2014). As pointed out by Urban, et al (2007) and Bhattachrayya and Timilsina (2010), existing models established for developed countries may not be appropriate for developing countries due to distinct issues and features. In the context of hydropower development in particular, unique issues and features to the developing countries include the equally important impact of agriculture, energy and flood on the economy, the heavy yield losses in both power and water distribution, and the time trade-off (induced by limited financial resources and the leading role of the government). These features are rarely studied in existing literature but can play a significant role in the expansion of hydropower networks. Our work extends the energy system planning literature to embrace connected issues in other sectors, such as irrigation and flood control, and captures the unique features of hydropower expansion in developing countries.

Operations research and operations management. As we discussed in Section 4.1.4, the flow control problem of a multi-reservoir system bears much similarity to the inventory control problem in multi-echelon inventory system (see, e.g., Zipkin 2000, Simchi-Levi and Zhao 2012). Specifically, the flow balancing model with evaporation loss is similar to a multi-echelon inventory model with external demand and supply at every stage where inventory is subject to deterioration proportional to the storage time. The water control problem in single dam under stochastic inflow is also studied in this literature, see Prabhu (1998). This paper uses the flow control model with predictable inflows and demand as a building block in the optimal expansion of the hydropower network.

The dynamic facility location problem with budget constraints provides many modeling techniques and solution approaches useful for our study, we refer the readers to Daskin, Snyder and Berger (2005), Snyder (2006) and Shen (2007) for thorough reviews of the literature. Rafique, Mun and Zhao (2015) develops a model to build up coal-fired energy supply chain under limited budget for energy security and economic prosperity. They consider both cost and time trade-offs in the energy sector and provide not only optimal but also politically feasible solutions.

This paper generalizes the energy supply chain concept from coal to hydro which encompasses much broader issues from energy to irrigation and flood control. These issues have synergies but also conflicts, and lead to different cost trade-offs. Specifically, rather than a balance between inbound and outbound costs for coal-fired energy supply chains, the cost trade-offs for a hydro supply chain are driven by the balance between economies of scale and yield losses, as well as conflicting development goals in different sectors. Second, hydro resource has different features and economics from coal, for instance, it does not have fuel transportation issues but the interaction of facilities and seasonally varying requirement. Third, the time trade-off is enriched from the energy-economy cycle (coal) to the water-economy cycle (hydro), where energy, agriculture (irrigation) and flood control all contribute significantly to the economy, but they share the water resources and pull hydropower locations in different directions. These new issues are further complicated by site-dependent type, cost, and time. In this paper, we build new models for hydro-resource planning of developing countries to capture the energy, irrigation and flood nexus. We produce new solutions and provide new insights on the relative performance among various popular but different practices.

Finally, recent research on socially responsible operations in this literature has shown great promises in both theory and practice. For instance, Dawande, et al. (2013) studies the efficiency and equity in irrigation water distribution between primary and secondary farms, and designs decentralized and individually rational mechanisms to achieve socially optimal distribution of surface water in a farming community. Our work expands and contributes to this growing body of knowledge by studying the interconnected issues of water, energy, food and flood in developing countries for the sustainable development of the economy.

4.3 Modeling Framework

In this section, we present our modeling framework for the hydro supply chain from interacting hydropower facilities to water and power distribution, and to diverse demand and flood zones. We shall first make assumptions and justify them by common practice and industry standard in Section 4.3.1, and then describe the mathematical model (namely, the cascading model) of flow control in Section 4.3.2. We next characterize the nexus of water, energy and flood in Section 4.3.3, and present a conceptual framework on the structure of the mathematical model in Section 4.3.4.

4.3.1 Assumptions and Justifications

Figure 4.3 provides an overview of the network structure.

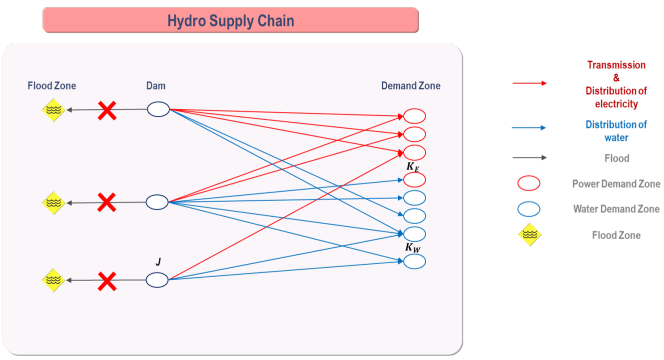


Figure 4.3: A model for hydro supply chain.

A hydro supply chain consists of the following key elements: the river system, hydropower network, distribution (power and water) networks, and demand and flood zones. The input to the river system (precipitation, surface and underground water) is exogenous and studied thoroughly by natural science disciplines, such as hydrology, meteorology and geology. The hydropower network (existing and potential sites) can be managed by either government agencies (e.g., WAPDA in Pakistan) or private companies (in developed countries). Likewise, power and water distribution can be managed by either public or private transmission, irrigation and utility companies.

We make the following general modeling assumptions.

Assumption 3. *General assumptions on the hydro supply chain:*

1. *The river system has a tree structure where potential hydropower locations are identified, indexed by $j \in \mathcal{J}_P$ where the set $\mathcal{J}_P$ has a cardinality J_P. For each location, there is an ideal type of hydrpower facility with known parameters such as construction cost and time, installed capacity (for power), storage capacity (for water) and energy convension rate (from water flow to energy generation). The existing hydropower facilities are indexed by $j \in \mathcal{J}_E$ (cardinality J_E) with known locations and parameters. Let $\mathcal{J} = \mathcal{J}_P \cup \mathcal{J}_E$ and J be the cardinality. We define segment j of the river system to be the river basin between location $j \in \mathcal{J}$ and all of its immediate upstream locations.*

2. *We consider a planning horizon of multiple periods (one period = a season = half year) as indexed by $t = 1, 2, \ldots, T$.*

3. *All major demand zones (each at a different location) are identified. There are two*

types of demand zones: Electricity demand zones, $\mathcal{K}_E$*, indexed by* $k = 1, 2, \ldots, K_E$*, and water demand zones (e.g., farmland),* $\mathcal{K}_W$*, indexed by* $k = 1, 2, \ldots, K_W$*. Demand (for electricity and water) is projected at each demand zone for each period of the planning horizon.*

4. *Water used for irrigation typically cannot be used for power generation and vice versa.*

5. *A hydropower site can serve any electricity demand zone but cannot supply water to a water demand zone (e.g., irrigating a farmland) too far upstream. An energy (water) demand zone can be supplied by multiple hydropower sites.*

6. *An annual (real) GDP depends strongly on power consumption, irrigation and flooded water in that year.*

7. *The public fund allocated to the development of hydropower system each year depends on the past year's real GDP.*

8. *The construction of a hydropower facility must be completed without preemption.*

9. *All non-hydropower related existing power supplies (e.g., oil and gas) and water supplies (e.g., wells and lakes) run as BAU (business as usual).*

The first assumption in Assumption 3 holds true in general for most developing countries. The potential sites for hydropower facilities and their parameters depend on many factors such as topography, geology, hydrology, and land use (Baban 2003). Each site is unique and ideal either for a dam or a barrage. For instance, barrage is generally built on flat terrain across wide and meandering rivers, while the best places for building a dam is a narrow part of a deep river valley. The second assumption is based on the monsoon seasons (or dry and rainy seasons) which take place in many developing countries in topical areas, ranging from south Asia, Sub-Saharan Africa, to Latin America. These seasons last from 4 months to 7 months and have clearly recognizable patterns of precipitation. The third assumption holds true because energy demand at an aggregated level of a demand zone follows a clear pattern that is documented and can be projected by the government. Similarly, the water demand (e.g., for irrigation) can be estimated at an aggregated level for each major farming area over each season by the government. The fourth assumption can be justified by the water resources management literature, please see O'Laoghaire and Himmelblau (1974), Grygier and Stedinger (1985), Cai, McKinney and Lasdon (2002), and Barber (2009). The fifth assumption holds because it is not practical for a hydropower facility to supply water to demand zones too far upstream due to significant energy required to pump up water, additional cost required to build temporary water storage sites, and yield (e.g., seepage) losses in water distribution.

To justify the sixth assumption, we first note that the dependence of economy (GDP) on energy consumption is well documented for Pakistan (Tang and Shahbaz 2013) and other countries around the world (Menegaki 2014). Second, agriculture often contributes significantly to the GDP for developing countries. Because irrigation is vital to agriculture output (Dawande 2013), thus it is critical to the GDP. Third, flood damage reduces GDP - a fact well studied for Pakistan in particular (Asian Development Bank 2013) and other countries in general (Shabnam 2014). The strong dependence is verified by our empirical study based on Pakistan's data (Section 4.5). The seventh assumption comes from the government's public funding allocation practice (Federal Budget Publications of Pakistan 2014-15). In each year, a certain percentage of the total available fund is allocated to the hydropower sector, where the total amount depends on the economic status (GDP), and the percentage depends on competing priorities and has to be decided by the government. We use real GDP to eliminate the impact of inflation. The eighth assumption is made based on the current practice in Pakistan (via communication with WAPDA) and for convenience. We make the last assumption to focus on hydropower development.

4.3.2 The Cascading Model

The cascading model (or flow balance model) is developed and studied in the water resource management literature, see Windsor (1973) and Grygier and Stedinger (1985). Because of the central role that it plays in the optimization of the much broader hydropower development problem, we present a concise expression of this model for river systems of a general topology.

We make the following assumptions.

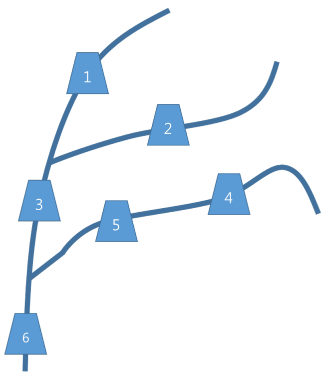
Assumption 4. *Water flow assumptions:*

1. *The net (external) inflow at each segment of the river, including local precipitation, underground and surface water (but not water from the upstream of the river system) less leakage, can be forecasted for each period of the planning horizon.*

2. *Evaporation loss of stored water in dams (with reservoir) cannot be ignored but such loss of running rivers can be ignored.*

To justify the first assumption in Assumption 4, we note that governments typically have detailed meteorological and hydrological data, based on which one can estimate the net external inflow for each period at each segment of the river system. The second assumption is valid because the annual evaporation loss of stored water in dams can be 40% in topical areas (Miller 2005, O'Laoghaire and Himmelblau 1974). However, evaporation loss of running water in rivers is negligible due to their short time of exposure. For instance, a running river at a normal speed of 5 miles a hour just takes 200 hours (less than 10 days) to cross 1000 miles.

To present the cascading model in a general structure river system, we introduce a concise notation - the adjacent matrix. For each hydropower location $j \in \mathcal{J}$, we identify the immediate upstream locations $j' \in \mathcal{J}$ by a matrix, X, of the following form: for $j' \neq j$, $X_{j,j'} = 1$ if j' is an immediate upstream location of j, $X_{j,j'} = 0$ otherwise. Figure 4.4 shows an example of a river system with multiple branches and hydropower sites, and the corresponding $X_{j,j'}$.



$X_{j,j'}$	1	2	3	4	5	6
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	1	1	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	1	0	0
6	0	0	1	0	1	0

Figure 4.4: An example of a river system and the $X_{j,j'}$.

In general, $X_{j,j'}$ can be written as

$$X_{j,j'} = \begin{cases} 0 & \text{if } j \text{ is at the most upstream,} \\ > 1 & \text{if } j \text{ is at a merged point of multiple branches,} \\ 1 & \text{otherwise.} \end{cases} \tag{4.1}$$

We now introduce notation. We follow the convention of using upper-case letters for parameters and lower-case letters for variables.

- $A_{j,t}$: Net external inflow to segment j of the river system (that is, the river basin between location j and all of its immediate upstream locations) in period t.
- η: The yield after accounting for evaporation loss for the stored water in reservoirs for a period.
- $s_{j,t}$: The stored water at location j at the end of the period t.
- C_j: The (water) storage capacity of the facility in location j.
- $u_{j,k,t}$: Water used (withdrawn for irrigation, etc.) in the period t from location j for demand zone k.
- $q_{j,t}$: Total water flowing into location j in period t.
- $o_{j,t}$: Total water flowing out of location j in period t to the river downstream; note that $o_{j,t}$ does not include $u_{j,k,t}$.

To write out the flow balance equation at location j, we consider two cases: If a hydropower facility is in operation at location j in period t, then the water flow into location j is,

$$q_{j,t} = \sum_{j'} X_{j,j'} \times o_{j',t} + A_{j,t}. \tag{4.2}$$

Water stored at location j at the end of period t is,

$$s_{j,t} = \eta \times (s_{j,t-1} + q_{j,t} - o_{j,t} - \sum_{k} u_{j,k,t}), \quad s_{j,t} \leq C_j. \tag{4.3}$$

If a hydropower facility is yet in operation at location j in period t, then

$$o_{j,t} = q_{j,t}, \quad , s_{j,t} = u_{j,k,t} = 0 \text{for all} k. \tag{4.4}$$

4.3.3 The Water, Energy and Flood Nexus

We first discuss the model for flood and its connection to the cascading model.

Assumption 5. *Flood control assumptions:*

1. *Because all flood zones are located next to the rivers, we group flood zones near location j and denote them by flood zone j. We assume flood zone j can only be affected by the upstream (but not downstream) hydropower facilities of location j.*

2. *Each flood zone has a tolerable peak flow per period; exceeding which results in flood.*

3. *All flooded water in flood zone j eventually flow back to rivers (to location j).*

The first assumption in Assumption 5 is made without loss of generality as the flooding areas are mostly affected by rivers nearby and we have the flexibility of grouping the flood areas. The peak tolerance per period serves as a proxy for the maximum flow that can pass location j without causing flood. The third assumption follows research in irrigation and hydrology (see, e.g., Ali 1993).

For the flood zone associated with location j, we define MT_j to be the peak tolerance (in billion cubic meters) per period. Because $q_{j,t}$ is the total amount of water flowing by flood zone j in period t; if $q_{j,t} > MT_j$, then flood occurs at flood zone j in the amount of $f_{j,t} = q_{j,t} - MT_j$. Otherwise, i.e., $q_{j,t} \leq MT_j$, there is no flood in flood zone j.

We then discuss the model for water supply (e.g., irrigation).

Assumption 6. *Water supply (irrigation) assumptions:*

1. *The water distribution system, e.g., canals and pipes, has been established and operative. Thus we only need to build passages for each new hydropower facility to connect it to the nearest water distribution system.*

2. *There is a upper limit on the amount of water that can be withdrawn at each hydropower location.*

3. *Loss and leakage (e.g., seepage, technical loss) in water distribution is non-negligible and distance dependent. The yield is γ per 100 miles.*

The first assumption in Assumption 6 holds true in Pakistan and many developing countries where agriculture contributes significantly to the GDP and irrigation systems are established. The second assumption is based on the capacity limits of canals and pipelines (Barber 2009). The third assumption comes from the statistics of significant losses in water delivery and irrigation distribution (FAO, M.J. Solomon 1998, Miller 2005). Thus, suppose $u_(j, k, t)$ is withdrawn from location j for water demand zone k, then only $\gamma^{D_{j,k}} \times u_(j, k, t)$ can reach zone k where $D_{j,k}$ is the distance between j and k (in 100 miles).

We lastly discuss the model for power supply.

Assumption 7. *Power supply assumptions:*

1. *Transmission system has been installed and operative. Thus we only need to build grid stations at each potential location and hook them up with the nearby transmission system.*

2. *The power generation at location j is proportional to $o_{j,t}$ as determined by the conversion ratio and bounded by the installed generating capacity.*

3. *The distribution of power via transmission systems is subject to yield loss, and the yield is ω per 100 miles.*

The first assumption in Assumption 7 holds true in Pakistan and many developing countries. The second assumption follows the fourth general assumption in Assumption 3. This assumption is also based on the fact that hydropower generation depends on both water head and water flow, and the conversion ratio connects the water flow with power generation. The yield loss in power transmission is well studied, see Hurlbut (2012). Thus, suppose $p_{j,k,t}$ is the power supplied from location j to power demand zone k, then only $\omega^{D_{j,k}} \times p_{j,k,t}$ can reach and be consumed by zone k. It is easy to see that consecutive hydropower facilities on the same river can interact with each other because more water stored or withdrawn (used) at one facility leads to less water flowing to all downstream facilities.

Figure 4.5 summarizes the water, energy and flood nexus in the context of hydropower.

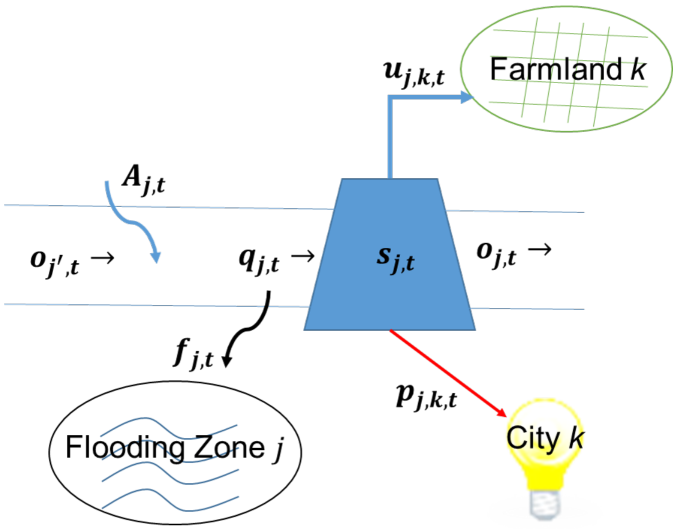


Figure 4.5: The water, energy and flood nexus in the context of hydropower.

4.3.4 The Conceptual Framework

We shall describe the key components of the mathematical model and their connections here before providing the full detail of the mathematical programming formulation in Section 4.4.

As discussed in Section 4.1.3, we take the standpoint of the government in this paper. Thus our ultimate objective is economic prosperity of the country, to which all sectors (energy, agriculture and flood control) contribute. To this end, we shall set the objective of our mathematical model to maximize the total discounted real GDP over a given planning horizon. GDP unifies the development goals across different sectors by dollar value, and is one way to represent the overall benefits of the system. The dependence of GDP on energy consumption, irrigation (through agriculture) and flooded water is justified in Assumption 3 and verified by a multiple regression model for Pakistan (Section **??**).

The mathematical model involves the following decision variables: when to set up which hydropower facility, which facility supplies which energy and water demand zones, water control decisions (store, withdraw and release) at each facility in operation.

The **constraints** are grouped by echelons and sectors.

1. **Flow control constraints**: The cascading model on water flow (e.g., flow balance equations, water storage capacity).

2. **Hydropower plant constraints**: A hydropower facility can be set up only once at each potential location; capital cost calculations.

3. **Water supply constraints**: The system cannot supply more water than what is needed at each demand zone; water withdrawn at a location is subject to the availability of the facility and the capacity limit of the distribution system; other water distribution restrictions must also be honored.

4. **Power supply constraints**: The conversion of water flow into power; power generation at a location is subject to the availability of the facility and bounded from above by the installed capacity; network constraints to connect power generated, power distributed to, and power demanded from all energy demand zones.

5. **Flood constraints**: To calculate the flooded water in each flood zone.

6. **Budget constraints**: The budget is limited and depends on the GDP.

The flow control constraints connect all hydropower facilities on the river system where adding one facility affects the operations and performance of all others. The water, power and flood constraints bridge the hydropower expansion decisions with distribution (water and power) decisions to the demand zones and flood damages to flood zones. These constraints also link water flow with power generation and flood and account for the unique features, capacity limits and demand requirement of different sectors. The hydropower plant constraints provide regularity conditions on the expansion of hydropower network and calculate the capital expenditures. Finally, the budget constraints connect past GDP with available funding for future development of the hydropower network.

The mathematical model is challenging to solve as even the optimal control of multi-reservoir systems (a subproblem) requires sophisticated optimization tools (Yeh 1985). We shall construct a mixed integer and linear programming model (MILP) in Section 4.4 to solve this problem.

4.4 Mathematical Programming Formulation

In this section, we present the mathematical programming formulation for the optimal design of hydro supply chains to meet multiple development goals from diverse demand and flood zones. We define indices in Table 4.1, which is followed by decision variables in Table 4.2 and intermediate variables in Table 4.3. All decision variables are non-negative. Note that T is an even number.

Index	**Name**	**Set**
j	Hydropower facility locations	$\mathcal{J} = \mathcal{J}_E \cup \mathcal{J}_P$
k	Electricity and water demand zones	$\mathcal{K} = \mathcal{K}_E \cup \mathcal{K}_W$
t or t'	time (unit: period = half a year or a year	$\{1, 2, ..., T\}$ or $\{1, 2, ..., T/2\}$

Table 4.1: Indices

Hydropower Facility			
$w_{j,t}$	1 if the facility in location j enters service	Binary	N/A
	in period t, 0 otherwise		
Water Control			
$o_{j,t}$	The amount of water released in period t	Continuous	Unit: Billion m^3
	from location j		
$u_{j,k,t}$	Water withdrawn at location j	Continuous	Unit: Billion m^3
	for demand zone k in period t		
$s_{j,t}$	Water stored at location j	Continuous	Unit: Billion m^3
	at the end of period t		
Power Supply			
$e_{j,t}$	Electricity generated at location j in period t	Continuous	Unit: MWh
$p_{j,k,t}$	Electricity supplied from location j	Continuous	Unit: MWh
	to demand zone k in period t		
Flood			
$f_{j,t}$	Flooded water at location j in period t	Continuous	Unit: Billion m^3

Table 4.2: Decision Variables

Hydropower Facility			
$q_{j,t}$	Water flow into location j in period t	Continuous	Unit: Billion m^3
$b_{j,t}^{HPP1}$	Cost to setup hydropower facility	Continuous	Unit: Million US $
	at location j in period t		$
b_t^{HPP2}	Total cost to operate hydropower facilities	Continuous	Unit: Million US $
	in period t		$
Budget and GDP			
$g_{t'}$	GDP in year t'	Continuous	Unit: Million US $

Table 4.3: Intermediate Variables

4.4.1 Objective Function

Let $\beta_{t'}$ be a series of time discounted factors decreasing in t' where t' is a time index in years (Table 4.1), then the objective function, i.e., the total discounted GDP over a finite planning horizon T, is,

$$\sum_{t'=1}^{T/2} \beta_{t'} \cdot g_{t'} \longrightarrow Max \tag{4.5}$$

where $g_{t'}$ can be written as follows,

$$\begin{aligned} g_{t'} \quad = \quad & g_{t'-1} + a_1 \cdot [\textstyle\sum_{j \in \mathcal{J}} \sum_{k \in \mathcal{K}_E} \frac{\Omega_{jk}}{2} (p_{j,k,2t'} + p_{j,k,2t'-1} - p_{j,k,2t'-2} - p_{j,k,2t'-3})] \\ & + a_2 \cdot [\textstyle\sum_{j \in \mathcal{J}} \sum_{k \in \mathcal{K}_W} \Gamma_{jk} \cdot (u_{j,k,2t'} + u_{j,k,2t'-1} - u_{j,k,2t'-2} - u_{j,k,2t'-3})] \\ & + a_3 \cdot [\textstyle\sum_{j \in \mathcal{J}} (f_{j,2t'} + f_{j,2t'-1} - f_{j,2t'-2} - f_{j,2t'-3})]. \end{aligned} \tag{4.6}$$

Here, $\Omega_{jk} = \omega^{D_{jk}}$ is the power transmission yield between location j and demand zone $k \in \mathcal{K}_E$, $\Gamma_{jk} = \gamma^{D_{jk}}$ is the water distribution yield between location j and demand zone $k \in \mathcal{K}_W$, and D_{jk} is the distance between j and k. Eq. (4.6) shows the dependence of the GDP on power consumption (first term), water consumption (second term) and flood (third term) through country-specific parameters, a_1, a_2, a_3, which can be estimated by empirical studies based on real data.

4.4.2 Flow Control Constraints

By the cascading model in Section 4.3.2, we have the following constraints on the inflow, storage, usage and outflow at each hydropower location.

$$q_{j,t} = \sum_{j'=1}^{J} X_{j,j'} \times o_{j',t} + A_{j,t}, \text{for } j \in \mathcal{J} \text{ and } t = 1, 2, ..., T, \tag{4.7}$$

and

$$s_{j,t} = \eta \times (s_{j,t-1} + q_{j,t} - o_{j,t} - \sum_{k \in \mathcal{K}_W} u_{j,k,t}), \text{ for } j \in \mathcal{J} \text{ and } t = 1, 2, ..., T, \tag{4.8}$$

and

$$s_{j,t} \leq C_j \text{ for } j \in \mathcal{J} \text{ and } t = 1, 2, ..., T. \tag{4.9}$$

The first two constraints connect different locations via the cascading model, the third constraint honors the water storage capacity at location j.

To ensure that Eq. (4.4) holds for non-operative locations, we also need,

$$s_{j,t} + \sum_{k \in \mathcal{K}_W} u_{j,k,t} \leq M \cdot \sum_{\tau=0}^{t} w_{j,\tau}, \text{ for } j \in \mathcal{J}_P \text{ and } t = 1, 2, ..., T, \tag{4.10}$$

where M is a constant selected for the big M method. This constraint implies that if there is no hydro-power facility in operations at location j, water can be neither stored nor withdrawn to meet demand.

4.4.3 Hydropower Plant Constraints

The first set of constraints for hydropower plants specifies their availability. Because a hydropower plant can only be setup once, thus

$$\sum_{t=1}^{T} w_{jt} \leq 1 \qquad \text{for} \quad j \in \mathcal{J}_P. \tag{4.11}$$

The second set of constraints for hydropower plants calculates their capital costs. For potential location $j \in \mathcal{J}_P$, the setup cost in period t (in million \$), b_{jt}^{HPP1}, can be written as follows,

$$b_{jt}^{HPP1} = IC_j \cdot \sum_{\tau=t+1}^{t+T_j} w_{j\tau} \qquad \text{for} \quad j \in \mathcal{J}_P \quad \text{and} \quad t = 1, \ldots, T - T_j, \tag{4.12}$$

where IC_j is the capital investment per period for setting up the hydropower facility at location j assuming that the total investment is evenly distributed over all periods of the project duration T_j.

Because setting up the hydropower facility takes multiple periods, it is logical to assume that we cannot start setting up the project at location j after the $T - T_j$th period as the facility will be ready beyond the planning horizon and thus cannot contribute to the objective function. Therefore the ending conditions for location $j \in \mathcal{J}_P$ are

$$b_{jt}^{HPP1} = IC_j \cdot \sum_{\tau=t+1}^{T} w_{j\tau} \qquad \text{for} \quad j \in \mathcal{J}_P \quad \text{and} \quad t = T - T_j + 1, ..., T - 1, \tag{4.13}$$

and

$$b_{jT}^{HPP1} = 0 \qquad \text{for} \quad j \in \mathcal{J}_P. \tag{4.14}$$

Finally, the operating cost of all hydropower facilities in year t, b_t^{HPP2}, is given by

$$b_t^{HPP2} = \sum_{j \in \mathcal{J}_P} OC_j \cdot \sum_{\tau=1}^{t} w_{j\tau} + \sum_{j \in \mathcal{J}_E} OC_j \qquad \text{for} \quad t = 1, \ldots, T, \tag{4.15}$$

where OC_j is the operating cost of the hydropower facility at location j per period. Note that while b_t^{HPP2} includes the operating costs of both existing and newly built facilities.

4.4.4 Water Supply Constraints

The first set of constraints for water supply ensures that the total amount of water supplied to each demand zone is less than the amount of water demanded. Let G^W_{kt} be the gap (or shortage) in water demand at demand zone k in period t, then

$$\sum_{j \in \mathcal{J}} \Gamma_{jk} \cdot u_{j,k,t} \leq G^W_{kt} \qquad \text{for} \quad k \in \mathcal{K}_W \quad \text{and} \quad t = 1, \ldots, T, \tag{4.16}$$

where Γ_{jk} is the yield (due to leakages and losses) in water distribution from location j to demand zone k (see Section 4.4.1).

The second set of constraints for water supply captures the special restrictions in water distribution, such as, a hydropower location cannot serve a water demand zone too far upstream (Assumption 3). We define the water distribution feasibility matrix Y_{jk}, where $Y_{jk} = 0$ implies that it is infeasible to supply water from j to k, $Y_{jk} = 1$ otherwise. Thus,

$$u_{j,k,t} \leq M \times Y_{jk} \qquad \text{for} \quad j \in \mathcal{J} \quad \text{and} k \in \mathcal{K}_W \quad \text{and} \quad t = 1, \ldots, T, \tag{4.17}$$

where M is a constant selected for the big M method.

The third set of constraints is on the capacity limits of the water distribution system at each location. Let r_j be the maximum fraction of the water flow into location j that can be withdrawn, then

$$\sum_{k \in \mathcal{K}_W} u_{j,k,t} \leq r_j \times q_{jt} \qquad \text{for} \quad j \in \mathcal{J} \quad \text{and} \quad t = 1, \ldots, T. \tag{4.18}$$

4.4.5 Energy Supply Constraints

The first set of constraints for energy supply specifies how electricity generation at hydropower location j is connected to the availability of the facility at this location, the installed capacity, and water flow released (the outflow).

$$\begin{aligned} e_{jt} &\le PC_j \cdot \textstyle\sum_{\tau=1}^{t} w_{j\tau} \qquad \text{for} \quad j \in \mathcal{J}_P \quad \text{and} \quad t = 1, \ldots, T, \\ e_{jt} &\le PC_j \qquad \text{for} \quad j \in \mathcal{J}_E \quad \text{and} \quad t = 1, \ldots, T, \end{aligned} \tag{4.19}$$

where PC_j is the installed capacity (for electricity generation) of the hydropower facility at location j.

$$e_{j,t} \le CR_j \times o_{jt} \qquad \text{for} \quad j \in \mathcal{J} \quad \text{and} \quad t = 1, \ldots, T, \tag{4.20}$$

where CR_j is the water-energy conversion ratio at location j. This constraints implies that the electricity generated at location j in period t is proportional to the amount of water released, o_{jt}.

The second set of constraints for energy supply links energy generation, energy distribution and consumption.

$$\sum_{k \in \mathcal{K}_E} p_{jkt} \le e_{jt} \qquad \text{for} \quad j \in \mathcal{J} \quad \text{and} \quad t = 1, \ldots, T. \tag{4.21}$$

This constraint implies that electricity supplied from location j can't be greater than the amount of electricity generated at j.

$$\sum_{j \in \mathcal{J}} \Omega_{jk} \times p_{jkt} \leq G^E_{kt} \qquad \text{for} \quad k \in \mathcal{K}_E \quad \text{and} \quad t = 1, \ldots, T, \tag{4.22}$$

where Ω_{jk} is the yield loss of energy transmission from j to k (see Section 4.4.1), and G^E_{kt} is the gap (or shortage) at energy demand zone k in period t. This constraint indicates that the electricity supplied to a demand zone cannot be greater than the amount demanded.

4.4.6 Flood Constraints

The flood constraint compares the water flow and the peak tolerance level at each flood zone to calculate the flood. By Section 4.3.3, the flooded water at flood zone j is $f_{jt} = \max\{0, q_{jt} - MT_j\}$. Thus, we have the following constraint,

$$f_{jt} \geq q_{jt} - MT_j \qquad \text{for} \quad j \in \mathcal{J} \quad \text{and} \quad t = 1, \ldots, T. \tag{4.23}$$

This constraint is valid because minimizing the flooded water helps to optimize the objective function.

4.4.7 Budget Constraints

The budget constraints limit the total spending on hydro supply chains (development and operations) in each year by a percentage of GDP in the past year.

$$
\begin{aligned}
\textstyle\sum_{j\in\mathcal{J}_P}(b_{j,1}^{HPP1}+b_{j,2}^{HPP1})+b_1^{HPP2}+b_2^{HPP2} &\leq g_0\cdot RA_1, \\
\textstyle\sum_{j\in\mathcal{J}_P}(b_{j,2t'}^{HPP1}+b_{j,2t'-1}^{HPP1})+b_{2t'}^{HPP2}+b_{2t'-1}^{HPP2} &\leq g_{t'-1}\cdot RA_{t'} \qquad \text{for} \quad t'=2,\ldots,T/2,
\end{aligned}
\tag{4.24}
$$

where $RA_{t'}$ is the ration in year *t'*, that is, the % of GDP allocated to the hydropower sector for development and operations; $g_{t'}$ is the real GDP in year t'.

4.5 Numerical Study

In this section, we apply the mathematical model (see Section 4.4) to Pakistan to generate solutions, demonstrate their potential impact and develop insights. Section 4.5.1 presents the real-life situations of Pakistan, and Section 4.5.2 provides solutions and insights.

4.5.1 The Case of Pakistan

A map of Pakistan's existing and potential hydropower sites and major demand and flood zones is shown in Figure 4.2. Working closely with Pakistan government through WAPDA, we collect comprehensive data and facts, and make the following observations.

Observation 1. *Observations on the hydro supply chain of Pakistan:*

1. *Pakistan has one major river system, the Indus. With many branches running from the world's highest mountain in the north to the Arabian sea in the south*

within about 1000 miles. There are 17 existing hydropower facilities, 6 storage dams and 11 non-storage barrages. Although more than 800 hundred potential projects along the Indus river and its branches have been identified, a majority have mini-capacity and incomplete study. We identified 41 locations with complete information (new construction not upgrading) and likely to be implemented in the near future, of which, 13 are storage dams and 28 are non-storage barrages. Thus $J = 58$*. Through WAPDA and research, we can identify all parameters, such as the latitude and longitude, cost, time, capacities, convension ratio, etc. for all locations.*

2. *There are 19 energy demand zones that account for 90% of the country's total energy consumption (Figure 4.2),* $K_E = 19$*. In Pakistan, irrigation related fresh water withdrawn accounts for 93.5% of the total (World Bank 2015), thus we shall only consider farmland (irrigation) as water demand zones. There are 15 major farming areas in Pakistan (see Figure 4.2) scattered across the entire country. Thus,* $K_W = 15$*.*

3. *Pakistan has quite uneven annual precipitation across the country with heavy rainfall in the northern mountain areas, which gradually decrease as we move to the southern Indus river floodplains, and then increase again close to the coast of Arabian sea. Many areas of this country experience clear patterns of seasonal rainfall between summer (June-November) and winter (December-May). In some areas, the rainy season could account for 80-90% of the annual precipitation. From the*

record of the government, we can estimate the external inflow at each segment of the river system.

4. *Energy demand varies across seasons. For instance, in 2012, the summer (rainy) season consumes about 16000 MWh while the winter (dry) season consumes about 12000 MWh. The pattern is quite repetitive in the history. In the current energy mix, hydropower (from existing facilities) accounts for about 31% of the 10000 MWh consumption. Demand for energy is estimated to grow at a rate of 5-7% annually (Alter and Syed 2011). Thus, the demand for hydropower (both existing and new) includes its current contribution to the energy mix and the projected energy shortfall.*

5. *Agriculture water consumption projections are made from 2010 thoughout 2025 by Pakistan Ministry of planning, development and reform. 29% of the agriculture water comes from the canal systems that connect the farmland with the hydropower facilities on the rivers (FAO 2011). Other sources of agriculture water include undergound water (wells) and surface water (lakes). Thus, the demand for irrigation water from the hydropower network include its current contribution to the agriculture sector and the projected water shortfall.*

6. *Irrigation water distribution is subject to significant losses, such as seepage and technical losses. FAO statistics in general (Solmon 1998) and Pakistan studies in particular (Yu, et al. 2015) show that such losses amount to about 15% water withdrawn. Given an average traveling distance of irrigation water of about 33*

miles in Pakistan, we estimate that the 100 miles yield loss is about 45% (thus, $\gamma = 55\%$).

7. *Evaporation of stored water in reservoirs causes about 40% annual loss in tropical areas (Miller 2005, O'Laoghaire and Himmelblau 1974). Thus, we estimate a 20% evaporation loss per period (half a year) in our study (thus, $\eta = 80\%$).*

We consider planning horizons of 20 years ($T = 40$, Padula 2015).

Table 4.4 specifies the model parameters for Pakistan.

Hydropower Facility:		
$A_{j,t}$	Net external inflow to segment j of the river system in period t	Unit: Billion m^3
T_j	Setup time for the hydropower facility at location j	Unit: period
IC_j	Setup cost for the hydropower facility at location j	Unit: million US \$
OC_j	Annual operating cost of the hydropower facility at location j	Unit: million US \$
PC_j	Installed capacity (electricity) of the hydropower facility at location j	Unit: MWh
CR_j	Conversion ratio of the hydropower facility at location j	Unit: MWh / Billion m^3
C_j	The storage capacity of the hydropower facility at location j	Unit: Billion m^3
$X_{j,j'}$	Immediate upstream matrix of locations	Binary
Power Supply:		
ω	% yield in power transmission per 100 miles	95.5%
Ω_{jk}	Transmission yield in % between location j and demand zone k	$\Omega_{jk} = \omega^{D_{jk}}$
G^E_{kt}	Energy gap at demand zone $k \in \mathcal{K}_E$	Unit: MWh
Water Supply:		
γ	% yield in irrigation distribution per 100 miles	55%
Γ_{jk}	Water distribution yield in % between location j and demand zone k	$\Gamma_{jk} = \gamma^{D_{jk}}$
η	% yield by evaporation for stored water in reservoir per period	80%
r_j	% of total flow into location j that can be withdrawn for usage	31%
G^W_{kt}	Demand gap at water demand zone $kin\mathcal{K}_W$ in period t	Unit: Billion m^3
$Y_{j,k}$	Water distribution feasibility matrix	Binary
Flood:		
MT_j	Peak tolerance flow in one period to prevent flood at location j	Unit: Billion m^3
Miscellaneous:		
$RA_{t'}$	Ration in year t'. i.e. % of GDP	Unit: %
$\beta_{t'}$	Discount factor in year t'	Unit: %
D_{jk}	Distance between location j and demand zone k	Unit: 100 *miles*
M	A real number large enough for the Big-M method	N/A

Table 4.4: Parameters for Pakistan's hydro supply chain.

Note that the hydropower setup cost, IC_j, includes cost of transmission line and grid station that connect the hydropower facility to the nearest transmission system. It also includes the cost of water passages that connect the facility to the nearest canal system. All other parameters of hydropower facilities can be extracted from feasibility studies and government research reports. Pakistan's current transmission systems use the alternating current (AC) technology (National Transmission and Despatch Company 2014). Despite recent studies of the direct current (DC) technology, it is unlikely to be implemented in the next 15-20 years due to the high cost and risk (Weedy, et al. 2012). Based on the voltages used in Pakistan, we conservatively estimate the yield loss per 100 miles, $(1 - \omega)$, to be 4.5% (Hurlbut 2012).

The energy and water gaps (shortages) at each demand zone are calculated based on government's estimate of future demand and items 4-5 in Observation 1. r_j is determined by the general statistics for the limit on water withdrawn at hydropower locations (Barber 2009). The water distribution feasibility matrix, $Y_{j,k}$, is determined by Assumption 3 where $Y_{j,k} = 0$ if the water demand zone k is upstream of location j by more than 200 miles. The MT_j can be estimated by the average flow per period at location j plus a location dependent buffer (from government's statistics). Our empirical study (multiple linear regression) of Pakistan's data from year 1972 to 2013 shows a strong dependence of the real GDP on energy consumption, irrigation water and flooded water ($R^2 = 0.999$). We estimate $a_1 = 12.224$, $a_2 = 135.439$, $a_3 = -71.196$ with p-value of 2.66E-06, 1.9E-11 and 0.008 respectively. We select 2011 as the starting year ($t = 0$) with a GDP $g_0 = 133,000$ (in *million \$*), a peak demand (summer peak load) of $16,000$ MWh and an energy gap of $6,000$ MWh (Kessides 2013). The initial condition $p_{j,k,0}, p_{j,k,-1}, u_{j,k,0}, u_{j,k,-1}, f_{j,0}, f_{j,-1}$ are determined by starting year 2011's data.

4.5.2 Solutions, Impacts and Insights

In this section, we present the optimal solutions generated by the mathematical models for Pakistan in various scenarios and compare them to two common practices similar to the government's plan on metrics such as net GDP (GDP less investment in hydropower sector, for economic growth), energy gap (for energy security), water gap (for irrigation), and flooded water (for flood control). We provide insights on how a hydropower network should be built up strategically under limited financial resource, the relative performance of various practices, and how system parameters may affect the results.

We consider two popular practices often found in developing countries. The first practice, namely practice 1, sorts the hydropower projects in the increasing order of the setup cost per unit of installed capacity, that is, total setup cost over installed electricity generating capacity. This practice starts construction of the projects following this order as long as the budget allows. The second practice, namely practice 2, sorts and starts construction of the hydropower projects in the decreasing order of the installed capacity. To ensure fairness in comparison, we applied the same procedure to optimize more tactic decisions, such as the flow control and water/power distribution decisions, in the optimal solution and the practices. Thus, the performance difference among them come from the strategic decisions on the selection of locations (projects) and the sequence of construction.

We consider scenarios under the following combinations of parameters: budget from 1%, 3%, 5%, 7% to 9% of real GDP, a planning horizon of 20 years (40 periods), and energy demand growth rate (5%). The water demand growth is estimated at 4.08%

(Mustafa 2013).

The mathematical model leads to large-scale multi-period mixed integer programs. For example, the scenarios of 20-year planning horizon have 16 constraints, 70,9927 continous variable and 1,253 binary variables. The mathematical program is solved by Gomory cutting planes method and implemented by a code written in Python version 2.75 and Gurobi Solver version 6.5. 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 within 2% of those of the optimal solutions. The computation time ranges from a few minutes to about a hour. All computations are done on a desktop computer with an Intel Xeon 2620 2.0 GHz and 36 GB RAM.

A Representative Example.

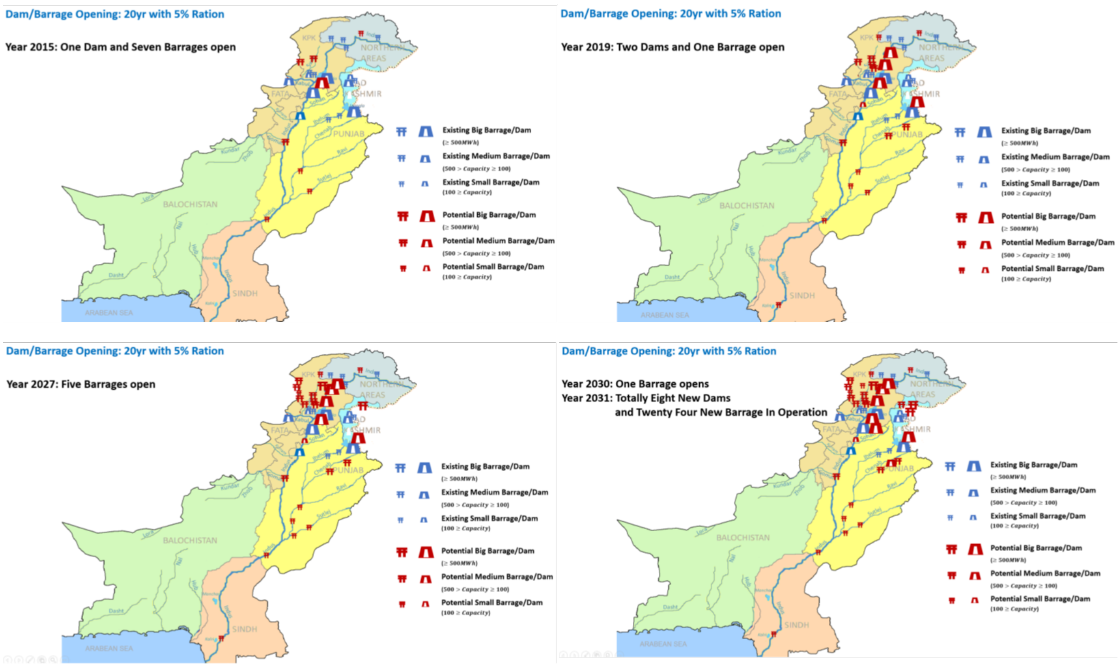


Figure 4.6: The optimal solution on the selection of hydropower sites and sequence of openning for the scenario with 5% demand growth, a budget of 5% GDP and a 20-year (40 periods) planning horizon.

The mathematical model provides intriguing solutions, which are structurally different from the popular practices. In the scenario of 5% demand growth, a budget of 5% GDP and a 40-period planning horizon, the optimal solution first opens a few small ($\leq$ 100 MWh) hydropower sites in the south (Sindh province) and north (Punjab province) but not far north, close to the major power and water demand zones in these provinces. Then it opens a large site ($\geq$ 500 MWh) in the north but not far north (Tarbela, near the capital city, Islamabad), and a medium site (between 100 MWh and 500 MWh) in Punjab. This is followed by a series of quick open-ups of small, medium and large sites scattered from northeast to northwest, from north to south, and from one branch to another of the Indus river. Although most of the largest sites (with also the lowest unit costs) are concentrated in the north and far north areas of the country, the optimal solution does not focus exclusively them, but blend them with small and medium sites from the south and areas between north and south. The location of a site is more important than its capacity or unit cost, because the optimal solution strategically spreads out the sites so that the demand zones can be evenly served over time and space. In this scenario, totally 33 new hydropower sites are opened over the planning horizon, and two of the top three largest sites are not among them (because they cost too much and take too long).

In comparison, practice 1 starts with a few largest sites in the north and far north, which exhausts all the budget in the first few years. Only after they are done (eight years after), the government then has the money to work on a few smaller sites with slightly higher unit cost. This is followed by other large and medium sites from diverse locations which open up gradually. In this practice, totally 25 new hydropower sites are opened in the planning horizon (the largest three sites are neither among them). Practice 2 opens fewer new sites (22 total) almost all towards the end of the planning horizon because it focuses on the largest sites (which cost the most and require the longest time). Because the top three largest sites exceed the budget limit, the practice starts with the fourth largest, which opens in the 14th year. This project exhausts all the budget for all these years and so government cannot work on other projects before this one is completed. It is only until the last few years of the planning horizon, a few more smaller sites can be opened.

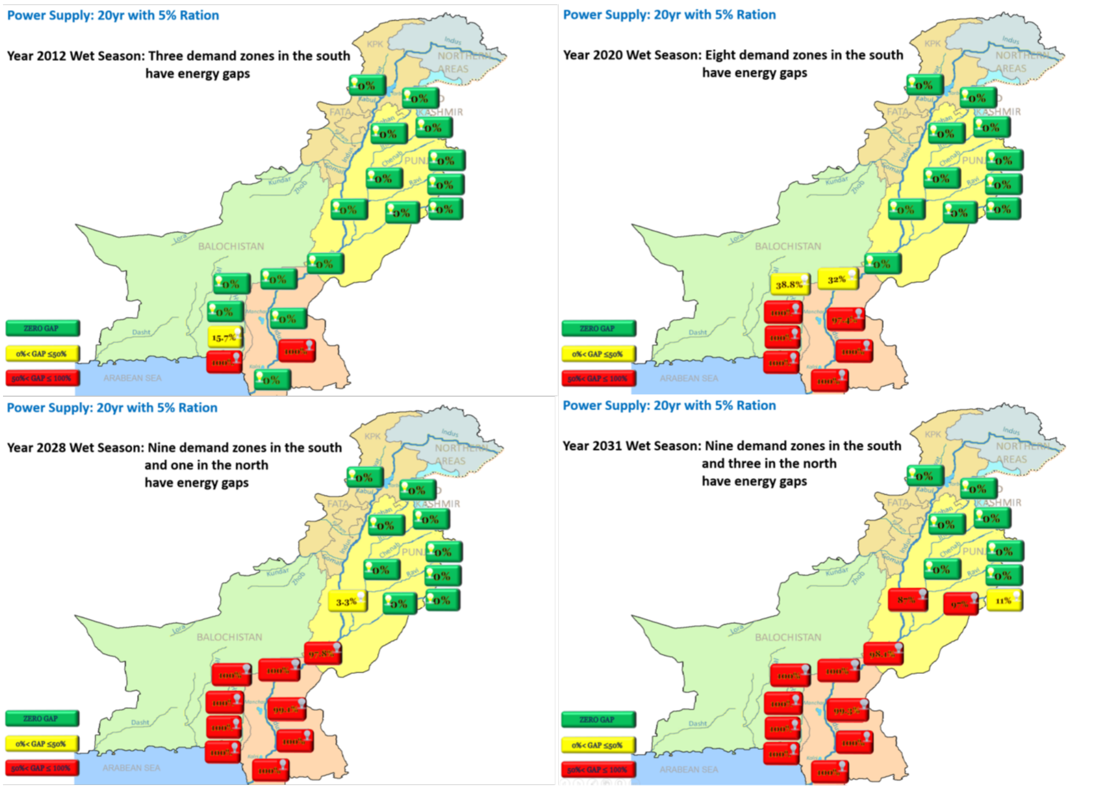


Figure 4.7: The optimal solution on energy gaps at demand zones for the scenario with 5% demand growth, a budget of 5% GDP and a 20-year planning horizon. Green - 0% gap, yellow - 1% to 50% gap, red - 51% gap and above.

In every period, the optimal solution provides more power supply compared to the the supply that practices provide.Especially the optimal solution gets to the zero power gap in many dry seasons. 5 years before the project ends, all of three models such as the optimal solution and two practices show the increase trend of power supply due to the higher demand than the total possible supply.

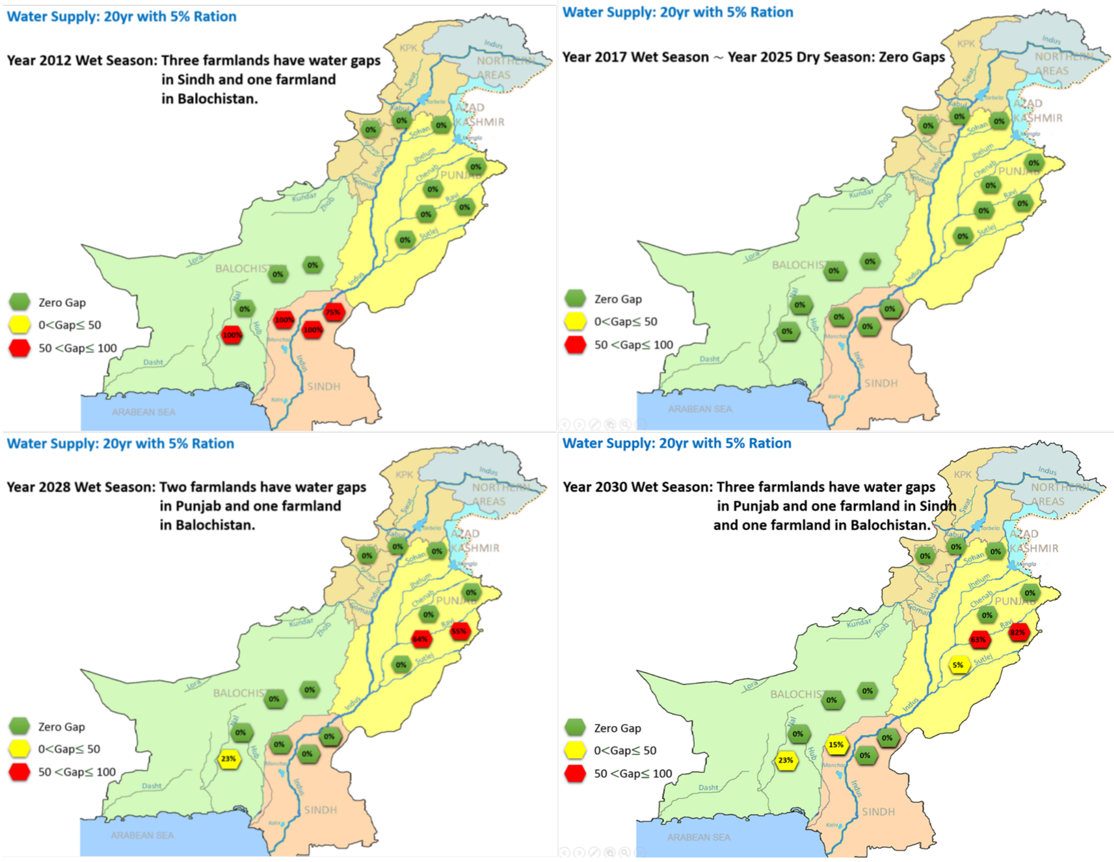


Figure 4.8: The optimal solution on water gaps at demand zones for the scenario with 5% demand growth, a budget of 5% GDP and a 20-year planning horizon. Green - 0% gap, yellow - 1% to 50% gap, red - 51% gap and above.

In most of dry seasons, the optimal solution makes zero water gap at all of 15 farmland compared to two practices, and few farmlands in the two far southern regions such as Sindh and Balochistan have water gaps due to the limited feasibility of possible local dam or barrage in those regions. The optimal solution gives zero water gaps for 7 years, but two practices make increasing water gaps over time.

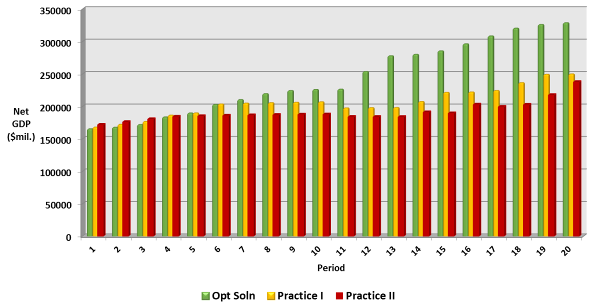


Figure 4.9: Optimal solution vs. practices. The x-axis is on time (in year). 5% demand growth, 5% ration and 20-year planning horizon.

To quantify the impact, we compare the optimal solution and the popular practices on four metrics: net GDP (Figure 4.9), % energy demand gap, % water demand gap, and flood (Figure 4.10).

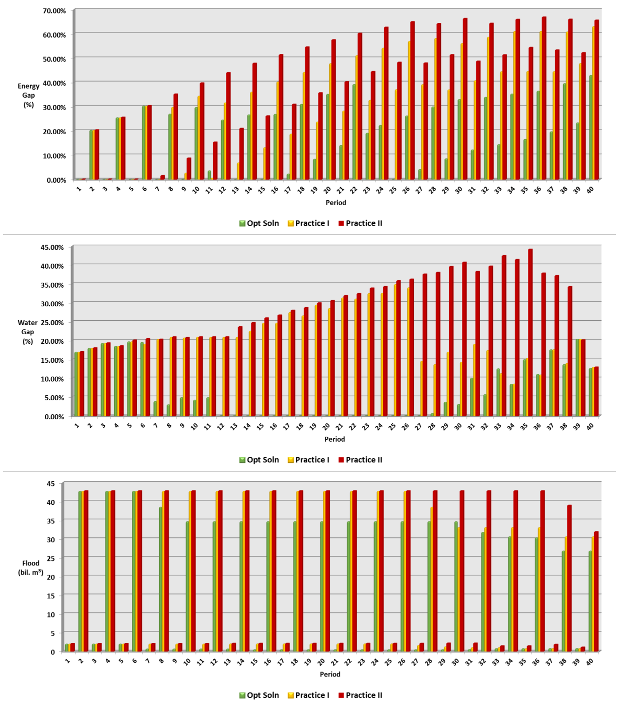


Figure 4.10: Optimal solution vs. practices. The x-axis is on time (in period). 5% demand growth, 5% ration and 20-year planning horizon.

As we can see, the optimal solution significantly outperforms the practices by boosting the economy much stronger (Figure 4.9), by significantly improving the performance in all three sectors of energy consumption, irrigation and flood control (Figure 4.10). Specifically, in this scenario, the optimal solution can keep the energy gap below 30% for most periods in the planning horizon while the practices go above 30% or even 40% in most of the periods. The optimal solution can reduce the water gap to zero while the practices constantly keep a 20% to 40% water gap. Finally, the optimal solution can reduce flood by 10% on average relative to the practices.

Sensitivity Study

We study the robustness of the solutions and the impact of various system parameters such as budget (ration), planning horizon, and demand growth rate. For all scenarios examined, the optimal solution stay qualitatively the same in the selection of hydropower sites and the sequence of construction. The most notable difference in a scenario with a higher % of ration is that the energy and water gaps can reach zero towards the end of the planning horizon, and if budget is sufficiently high, the top three largest sites may be opened.

To study the impact of the budget ration, we plot the compounded GDP growth rate for the optimal solution and the two practices for different budget rations from 1% to 9% (Figure 4.11). The figure shows that although the optimal solution always outperforms the practices on GDP growth rate, it makes the greatest difference 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, the efficiency as achieved by the optimal solution becomes relatively unimportant as funding is abundant.

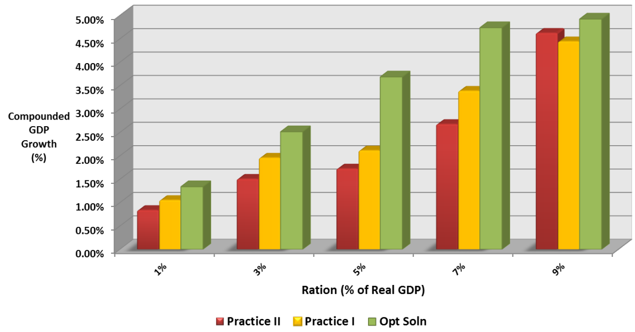


Figure 4.11: The compounded GDP growth rate for the optimal solution, practices 1 and 2 for various budget rations.

Insight on Popular Practices Our numerical studies and optimal solutions provide insights on the relative performance of many popular but opposite practices. First, location flexibility seems more valuable than the economies of scale in hydropower site selection because the practices focusing the latter perform much worse than the optimal solution. Second, neither the strategy of many small sites nor the strategy of a few large sites is the best, the optimal solution combines large and small sites and spread them out strategically to meet demand from diverse locations. Third, concentrated hydropower locations should be avoided as the optimal solution space out the sites both in space and time to maximize the benefits to the demand zones. Finally, storage dams and non-storage barrages should be mixed to achieve the best overall impact.

4.6 Conclusion

The interconnected issues of water, energy, food and flood lie at the center of the sustainable development of economy and society for many developing countries, such as those in South Asia, sub-Saharan Africa and Latin America. Hydropower development is an ideal solution as it is not only abundantly available in many of these countries but can also address all these issues in the same time. However, these countries typically have very limited budget and hydropower development takes a long time and costs a fortune. How to develop and expand hydropower network for developing countries with limited financial resource to address the nexus of water, energy, food and flood remains as a substantial challenge. In this paper, we construct a novel mathematical model to capture unique features of hydropower expansion in developing countries and to optimize the synergies and balance the conflict of the diverse development goals. Applying to the real life situation of Pakistan, we demonstrate the potential of the model in improving all sectors of energy consumption, irrigation and flood control, and thus ultimately, the economy.

Chapter 5

Future Research and Extensions

In this dissertation we studied strategic energy and water supply chain design in to figure out unique features and economics of energy and water supply related problems in context of logistic network design.

Countries in Africa, Asia, and other regions are more likely to suffer from energy poverty than enjoy economic prosperity. Like Gov plan of Pakistan, they try to make economy wealthier than before. But what does it mean for most of people who still live in energy poverty? It could not be realized with very limited budget. It doesn't have to be this way. Extreme energy poverty is far from being eliminated. Their story could be so different so that we focused turns from energy poverty to prosperity (security) as energy deficit ebbs in these countries, and our model tries to strategically integrates all of players such as fuel location, power plants, and demand zones for fully utilizing it at lower cost.

And in Hydro research, we construct a novel mathematical model to capture unique features of hydropower expansion in developing countries and to optimize the synergies and balance the conflict of the diverse development goals.

This work can be extended in a number of directions: First, the mathematical properties of hydro supply chains can be explored to enable more efficient solution algorithms. Second, we ignore political issues in hydropower network expansion, which may plays an important role in feasibility issues. Finally, we ignore all other power generation sources while planning for the hydro supply chain. It would be ideal to plan all sources of energy together - the energy mix planning.

Bibliography

[1] Ali, I. (1993). *Irrigation and Hydraulic Structures: Theory, Design and Practice.* Publisher, Institute of Environmental Engineering and Research, NED University of Engineering & Technology, Karachi, 1993, ISBN: 9698160000

[2] Prabhu, N.U. (1998). *Stochastic Storage Processes: Queues, Insurance Risk and Dams.* Second Edition, Springer-Verlag, New York.

Barber 2009, N.L. Barber, US Geological Survey Factsheet #3098

[3] ADB (Asian Development Bank, 2013). Indus Basin Floods. 2013. Asian Development Bank, Philippines.

[4] Alter, N. and Syed, S. H. (2011). An empirical analysis of electricity demand in Pakistan. *International Journal of Energy Economics and Policy*, 1(4):116–139.

[5] Ambrosino, D. and Grazia Scutellà, M. (2005). Distribution network design: new problems and related models. *European Journal of Operational Research*, 165(3):610–624.

[6] Azadeh, A., Ghaderi, S., and Maghsoudi, A. (2008). Location optimization of solar plants by an integrated hierarchical DEA PCA approach. *Energy Policy*, 36(10):3993–4004.

[7] Barda, O. H., Dupuis, J., and Lencioni, P. (1990). Multicriteria location of thermal power plants. *European Journal of Operational Research*, 45(2):332–346.

[8] Bhattacharyya, S., Timilsina, G.R. (2010). A review of energy system models. *International Journal of Energy Sector Management*, 4:494-518.

[9] Board of Investment Prime Minister's Office. (2014) Coal Based Projects. Board of Investment Prime Minister's Office, Islamabad, Pakistan.

[10] Bowen, B. H., Canchi, D., Lalit, V. A., Preckel, P. V., Sparrow, F., and Irwin, M. W. (2010). Planning India's long-term energy shipment infrastructures for electricity and coal. *Energy Policy*, 38(1):432–444.

[11] Canel, C. and Khumawala, B. M. (1997). Multi-period international facilities location: An algorithm and application. *International Journal of Production Research*, 35(7):1891–1910.

[12] Canel, C. and Khumawala, B. M. (2001). International facilities location: a heuristic procedure for the dynamic uncapacitated problem. *International Journal of Production Research*, 39(17):3975–4000.

[13] Chen, I. J. and Paulraj, A. (2004).Understanding supply chain management: critical research and a theoretical framework. *International Journal of Production Research*, 42(1):131–163.

[14] Chen, W. and Xu, R. (2010). Clean coal technology development in china. *Energy Policy*, 38(5):2123–2130.

[15] CIA. (2014). CIA world fact book, 2014. CIA, 2014

[16] Connolly, D., Lund. H., Mathiesen, B.V., Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, 87:1059–1082.

[17] Daskin, M. S., Snyder, L. V., and Berger, R. T. (2005). Facility location in supply chain design. In *Logistics systems: Design and optimization*, pages 39–65. Springer.

[18] Dias, J., Eugénia Captivo, M., and Clímaco, J. (2007). Efficient primal-dual heuristic for a dynamic location problem. *Computers & operations research*, 34(6):1800–1823.

[19] Drezner, Z. (1995) Dynamic facility location: The progressive p-median problem. *Location Science* 3 (1): 1-7.

[20] Dutton, R., Hinman, G., and Millham, C. (1974). The optimal location of nuclear-power facilities in the pacific northwest. *Operations Research*, 22(3):478–487.

[21] Earchscan, (2011). THE STATE OF THE WORLD?S LAND AND WATER RESOURCES FOR FOOD AND AGRICULTURE, New York.

[22] Eiselt, H. A., Vladimir M. (2011) Foundations of Location Analysis. Springer Science+Business Media, New York.

[23] FAO (Food and Agricultural Organization of the United Nations, 2009). Available at `<http://www.fao.org/news/story/en/item/35571/icode/>`.

[24] FAO (Food and Agricultural Organization of the United Nations, 2011). Irrigation in Southern and Eastern Asia in figures. Available at <http://www.fao.org/nr/water/aquastat/countries_regions/ind/ind-cp_eng.pdf>.

[25] FAO (Food and Agricultural Organization of the United Nations, 2014). Available at <http://www.fao.org/nr/water/aquastat/water_use/index.stm>.

[26] FAO (Food and Agricultural Organization of the United Nations, 2016). Available at <http://www.fao.org/nr/water/espim/country/pakistan/index.stm>.

[27] Federal Budget Publications 2014-15 (Ministry of Finance, Government of Pakistan, 2014). Available at <http://www.finance.gov.pk/fb_2014_15.html> (Retrieved on Oct 14, 2014).

[28] Fleischmann, B., Ferber, S., and Henrich, P. (2006). Strategic planning of BMW's global production network. *Interfaces*, 36(3):194–208.

[29] Geoffrion, A. M. and Graves, G. W. (1974). Multicommodity distribution system design by benders decomposition. *Management science*, 20(5):822–844.

[30] Global Methane Initiative. (2010). Coal mine methane country profiles. Global Methane Initiative, 2010

[31] Gen, M. and Syarif, A. (2005). Hybrid genetic algorithm for multi-time period production/distribution planning. *Computers & Industrial Engineering*, 48(4):799–809.

[32] Godoy, E., Benz, S., and Scenna, N. (2012). Optimal economic strategy for the multiperiod design and long-term operation of natural gas combined cycle power plants. *Applied Thermal Engineering*, 51:218–230..

[33] Halldorsson, A. and Svanberg, M. (2012). Energy resources: Trajectories for supply chain management. *Supply Chain Management: An International Journal*, 18(1):66-73.

[34] Harbert, Tam. (2014). Construction begins on $7 billion power Africa project. Available at spectrum.ieee.org/energy/policy/construction-begins-on-7-billion-power-africa-project. updated on Feb 21, 2014.

[35] Hasani, A., Zegordi, S. H., Nikbakhsh, E. (2012) Robust closed-loop supply chain network design for perishable goods in agile manufacturing under uncertainty. *International Journal of Production Research*, 50 (16): 46494669.

[36] Hinojosa, Yolanda and Puerto, Justo and Fernández, Francisco R. (2000). A multiperiod two-echelon multicommodity capacitated plant location problem. European Journal of Operational Research, 123(2): 271-291

[37] Hurlbut, D. (2012) Geothermal Power and Interconnection: The Economics of Getting to Market. National Renewable Energy Laboratory, The U.S. Department of Energy. April, 2012.

[38] IEA (International Energy Agency, 2006). Energy for cooking in developing countries. IEA (2006).

[39] IEA (International Energy Agency, 2011). World energy outlook. 2011. OECD Publications, Paris.

[40] IEA (International Energy Agency, 2013).Southeast Asia Energy Outlook. International Energy Agency, France, 2013

[41] IEA (International Energy Agency, 2011). Key world energy statistics. 2014. OECD Publications, Paris.

[42] IHA (International Hydropower Association, 2014). Types of hydropower. 2014. Available at `<https://www.hydropower.org/types-of-hydropower>`.

[43] IFC (International Finance Corporate, 2015). IFC Announces Financing Package to Expand Reach of Tanzanias Off Grid Electric.

[44] Iqbal, N., Nawaz, S., and Anwar, S. (2013). Electricity demand in Pakistan: A nonlinear estimation. Technical report, Mimeo Pakistan Institute of Development Economics.

[45] Kavouridis, K. and Koukouzas, N. (2008). Coal and sustainable energy supply challenges and barriers. *Energy Policy*, 36(2):693–703.

[46] Kermeliotis, T. (2013). Will 'world's biggest' hydro power project light up Africa?. CNN. Available at <http://www.cnn.com/2013/06/28/business/biggest-hydropower-grand-inga-congo/>.

[47] Kessides, I. (2013). Chaos in power: Pakistan's electricity crisis. *Energy Policy*, 55:271-285.

[48] Kiernan, P. (2014). Africa: Resource rich, energy poor. Available at <http://geafricaascending.economist.com/2014/07/31/africa-resource-rich-energy-poor/> (Retrieved on December 31, 2014).

[49] Klose, A. and Drexl, A. (2005). Facility location models for distribution system design. *European Journal of Operational Research*, 162(1):4–29.

[50] Kuby, M., Neuman, S., Zhang, C., Cook, P., Zhou, D., Friesz, T., Shi, Q., Gao, S., Watanatada, T., Cao, W., Sun, X., Xie, Z. (1993). A strategic investment planning model for China's coal and electricity delivery system. *Energy*, 18(1):l-24.

[51] Kugelman, M. (2013). Pakistan's energy crisis: From conundrum to catastrophe? Available at <http://www.nbr.org/downloads/pdfs/eta/Kugelman_commentary_03132013.pdf>. Retrieved on Jan 27, 2014.

[52] Liu, Y., Huang, G., Cai, Y., Cheng, G., Niu, Y., and An, K. (2009). Development of an inexact optimization model for coupled coal and power management in north china. *Energy Policy*, 37(11):4345–4363.

[53] Lewis, C. (2013). China?s Great Dam Boom: A Major Assault on Its Rivers. Available at <http://e360.yale.edu/feature/chinas_great_dam_boom_an_assault_on_its_river_systems/2706/>.

[54] Love, Robert F and Morris, James J and Wesolowsky, George O. (1988). Facilities location. Vol.90, North-Holland Amsterdam, 1988.

[55] Luo, T., Maddocks, A., Iceland, C. (2015). World?s 15 Countries with the Most People Exposed to River Floods. World Resources Institute, March 05, 2015, Available at <http://www.wri.org/blog/2015/03/world's-15-countries-most-people-exposed-river-floods>.

[56] Mai, T., Drury, E., Eurek, K., Bodington, N., Lopez, A., Perry, A. (2013). Resource planning model: an integrated resource planning and dispatch tool for regional electric systems. Technical Report NREL/TP-6A20-56723. National Renewable Energy Laboratory, Golden, Colorado, USA.

[57] Malik, A. (2008). How Pakistan is coping with the challenge of high oil prices. *The Pakistan Development Review*, 46(4):551–575.

[58] Malik, A. (2010). Oil prices and economic activity in Pakistan. *South Asia Economic Journal*, 11(2):223–244.

[59] Manan, A. (2014). energy Crisis: 'New coal power initiative to generate 6,000 MW'. The Express Tribune (with the International New York Times), Saturday, 08 Feb 2014.

[60] Mathur, R., Chand, S., and Tezuka, T. (2003). Optimal use of coal for power generation in India. *Energy policy*, 31(4):319–331.

[61] Mcjannet, D. (2013). Comparison of techniques for estimating evaporation from an irrigation water storage. *Water Resources Research*, 49(3):1415-1428.

[62] Meixell, M. J. and Gargeya, V. B. (2005). Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review*, 41(6):531–550.

[63] Melachrinoudis, E. and Min, H. (2000). The dynamic relocation and phase-out of a hybrid, two-echelon plant/warehousing facility: A multiple objective approach. *European Journal of Operational Research*, 123(1):1–15.

[64] Menegaki, A. N. (2014). On energy consumption and GDP studies; a meta-analysis of the last two decades. *Renewable and Sustainable Energy Reviews*, 29:31-36.

[65] Melo, M.T., Nickel, S., da Gamac, F. S. (2005) Dynamic multi-commodity capacitated facility location: a mathematical modeling framework for strategic supply chain planning. *Computers & Operations Research* 33: 181208

[66] Melo, M. T., Nickel, S., and Saldanha-Da-Gama, F. (2009). Facility location and supply chain management–a review. *European Journal of Operational Research*, 196(2):401–412.

[67] Min, H. and Zhou, G. (2002). Supply chain modeling: past, present and future. *Computers & Industrial Engineering*, 43(1):231–249.

[68] Mirchandani, Pitu B and Francis, Richard L. (1990). Discrete location theory. 1990

[69] Mustafa, D., Akhter, M., and Nasrallah, N. (2013). UNDERSTANDING PAKISTAN?S WATER-SECURITY NEXUS. United States Institute of Peace (2013).

[70] Muzamil, H. (2015). Pakistan's energy mix: power and politics. Dawn.com, Oct. 04, 2015, http://www.dawn.com/news/1210831/pakistansenergymixpowerandpolitics.

[71] Ministry of Pakistan Railway. Available at `<http://www.railways.gov.pk>` (Accessed on Feb 08, 2011).

[72] National Electric Power Regulatory Authority. (2012).State of Industry Report. Available at http://nepra.org.pk/industryreports.htm. Accessed on Feb 01, 2014.

[73] Narayan, P. K., Narayan, S., and Popp, S. (2010). A note on the long-run elasticities from the energy consumption–GDP relationship. *Applied Energy*, 87(3):1054–1057.

[74] National Transmission and Despatch Company. (2014). Power System Statistics 2013-2014. Available at <http://www.ntdc.com.pk/Files/39th.pdf> (Accessed on June 30, 2014).

[75] NEPRA (National Electric Power Regulatory Authority, 2011). State of industry report 2011. Available at <http://nepra.org.pk/industryreports.htm> (Retrieved on Feb 01, 2014).

[76] OECD (Organization for Economics Co-operation and Development, 2014). OECD Environmental Outlook to 2050. Available at <http://www.oecd.org/environment/nexus.htm>

[77] Owen, S.H., Daskin, M.S. (1998) Strategic facility location: A review. *European Journal of Operational Research*. 111(3): 423-447.

[78] Pakistan Railway Network Map by Adnanrail (2012). Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons. Available at <http://commons.wikimedia.org/wiki/File:Pakistan_Railways_Map.png> (Accessed on Dec 05, 2013).

[79] Paulus, M. and Trüby, J. (2011). Coal lumps vs. electrons: How do Chinese bulk energy transport decisions affect the global steam coal market? *Energy Economics*, 33(6):1127–1137.

[80] PPIB (Private Power and Infrastructure Board, 2011). Hudro power resources of Pakistan. Private Power and Infrastructure Board (1011).

[81] Rafique, R. and Zhao, Y. (2011). Pakistan Energy Crisis - Breaking the Vicious Cycle. Case Study, Rutgers Business School - Newark and New Brunswick. http://zhao.rutgers.edu/teaching.htm.

[82] Rafique, R., Kwon Gi Mun and Zhao, Y. (2015). Energy supply chain design: A dynamic model for energy security, economic prosperity, and environmental sustainability. Working paper, Rutgers Business School - Newark and New Brunswick.

[83] (Renewables First, 2016). How much hydropower power could I generate from a hydro turbine. Available at <https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-much-power-could-i-generate-from-a-hydro-turbine/>

[84] Rietveld, P. and Ouwersloot, H. (1992). Ordinal data in multicriteria decision making, a stochastic dominance approach to siting nuclear power plants. *European Journal of Operational Research*, 56(2):249–262.

[85] Rosnes, O. and Vennemo, H. (2012). The cost of providing electricity to Africa. *Energy Economics*, 34(5):1318–1328.

[86] Santana, R. (2013). Pakistan's power shortage problem is country's biggest threat. Available at <http://www.huffingtonpost.com/2013/06/15/pakistan-power-shortage_n_3447599.html> (Retrieved on Feb 01, 2014).

[87] Seckler, D., Molden, D. and Baker, R. (1998). World Water Demand and Supply, 1990 to 2025: Scenarios and Issues. International Water Management Institute, Sri Lanka.

[88] Shahbaz, M., Zeshan, M., and Afza, T. (2012). Is energy consumption effective to spur economic growth in Pakistan? New evidence from bounds test to level relationships and granger causality tests. *Economic Modelling*, 29 (6):2310–2319.

[89] Shapiro, J. F. (2007). *Modeling the supply chain*, volume 2. Cengage Learning.

[90] Shen, Z.-J. M., Coullard, C., and Daskin, M. S. (2003). A joint location-inventory model. *Transportation Science*, 37(1):40–55.

[91] Shen, Z. (2007). Integrated supply chain design models: A survey and future research directions. *Journal of Industrial and Management Optimization*, 3(1):1-27.

[92] Shu, J., Teo, C. P., Shen, Z. J. (2005). Stochastic Transportation-inventory Network Design Problem. *Operations Research*, 53: 48–60.

[93] Silva S. (1991). Dams: What They Are and What They Do. International Rivers (1991). Available at <https://www.internationalrivers.org/dams-what-they-are-and-what-they-do>.

[94] Snyder, L. V. (2006). Facility location under uncertainty: A review. *IIE Transactions*, 38(7):547–564.

[95] Sodhi, ManMohan S., Tang, C. (2014). Buttressing supply chains against floods in Asia for humanitarian relief and economic recovery. *Production and Operations Management*, 23(6):938–950.

[96] Solomon, K. (1998). Irrigation Notes, California State University, Fresno, California. Available at <http://www.kroyind.com/articles/waterefficiencies.htm>

[97] Solow, R. M. (1956). A contribution to the theory of economic growth. *The quarterly journal of economics*, 70(1):65–94.

[98] Susta, M. R. (2008). Development in Supercritical Steam Tech. *Powergen Asia 2008, Kuala Lumpur, Oct. 2008.*

[99] Tang, C. F. and Shahbaz, M. (2013). Sectoral analysis of the causal relationship between electricity consumption and real output in pakistan. *Energy Policy*, 60:885–891.

[100] The News International (2014). CM welcomes Chinese investment in coal mining. Tuesday, March 18. Available at <http://www.thenews.com.pk/> (Accessed on March 20, 2014).

[101] Troncoso, J. J. and Garrido, R. A. (2005). Forestry production and logistics planning: an analysis using mixed-integer programming. *Forest Policy and Economics*, 7(4):625–633.

[102] United Nations. (2013) World population prospects. U.N., New York, 2013.

[103] Urban, F., Benders, R.M.J., Moll, H.C. (2007). Modelling energy systems for developing countries. *Energy Policy*, 35:3473-3482.

[104] Van Roy, T. J. and Erlenkotter, D. (1982). A dual-based procedure for dynamic facility location. *Management Science*, 28(10):1091–1105.

[105] Vila, D., Martel, A., and Beauregard, R. (2006). Designing logistics networks in divergent process industries: A methodology and its application to the lumber industry. *International Journal of Production Economics*, 102(2):358–378.

[106] Weedy, B. M., Cory, B. J., Jenkins, N., Ekanayane, J. B., Strabac, G. (2012) Electric Power Systems, 5th edition, Wiley, United Kingdom.

[107] Wesolowsky, G. O. (1973). Dynamic facility location. *Management Science*, 19(11):1241–1248.

[108] Wesolowsky, G. O. and Truscott, W. G. (1975). The multiperiod location-allocation problem with relocation of facilities. *Management Science*, 22(1):57–65.

[109] World Energy Council. (2013). World energy resources: Coal. World Energy Council, 2013

[110] World Bank. (2012). The World Bank Data, Annual freshwater withdrawals, agriculture, (2015). Available at <http://data.worldbank.org/indicator/ER.H2O.FWAG.ZS/countries?display=map>.

[111] The World Bank. (2013).World Bank Data: GDP Ranking. 2013. Available at http://data.worldbank.org/data-catalog/GDP-ranking-table.

[112] The World Bank. (2013).Global Tracking Framework. The World Bank, 2012

[113] World Bank. (2015). The World Bank Data, Pakistan, (2012). Available at <http://data.worldbank.org/country/pakistan> (Accessed on Sep 27, 2013).

[114] World Energy Council. (2013). World Energy Resources: 2013 Survey, (2012). World Energy Council, London.

[115] Yusuf, H., Hasan, S. S. (2015). Conflict dynamics in Sindh. Peaceworks Report No. 104, United States Institute of Peace, Washington, DC.