Designing Energy Supply Chains: Dynamic Models for Energy Security and Economic Prosperity

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Abstract

Many developing countries suffer severe energy deficiencies despite their ample reserves of resources - the so-called predicament of "*resource rich, energy poor*." A leading driver is the energy-economy cycle, where poor economic status, inefficient utilization of limited budget, and energy deficiency reinforced each other and 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. We apply supply chain design and location optimization models to address the unique features of the energy sector in these countries and present a new class of mathematical models for designing coal-fired energy supply chains. The model captures the interaction among different parts of an integrated energy supply chain, the unique economics of power transmission such as yield losses, the political issues associated with equity, and the dynamic interaction among energy consumption, economy and budget. The model attempts to answer the classic question by determining the optimal and politically feasible ways to build up an energy supply chain under limited budgets for energy security and economic prosperity. Applying the model to Pakistan's recent energy crises, we show that the solutions can significantly outperform the government's plan by reducing the energy gaps faster, boosting the economy stronger with less greenhouse gas emissions. We develop insights on how an energy supply chain should be built up strategically for developing countries, and how various system parameters may affect the results.

Key words: Developing Countries; Energy Deficiency; Energy Supply Chain; Coal; Supply Chain Design and Optimization

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1 Introduction

1.1 Motivation

Many developing countries in Asia and Africa are bestowed with abundant hydrocarbon resources, e.g., coal (oil) reserves of India and Pakistan (Sudan) are among the largest in the world. However, these countries have the world's largest population denial of electricity access (International Energy Agency (IEA) 2011). The Economist (Kiernan 2014) called such a predicament "*resource rich, energy poor*".

One leading cause for the predicament is the energy-economy cycle. Electricity supply requires the build-up of an energy supply system from mines to power plants and to transmission networks. This is a formidable task that requires a significant and consistent investment over decades. Developing countries with high energy deficiency are often in deep debts and bear poor credit ratings, and thus can only secure limited budgets for energy infrastructure development. Limited funds along with their inefficient utilization result in ineffective energy supplies which further worsen the economic status and budgetary situation. Thus, the poor economy, inefficient use of limited budgets, and energy deficiency interact with each other and often led these countries into a spiral of economic downfall (Figure 1). In addition to stagnated economic growth or recession, severe energy deficiency can be disastrous as it often drives up unemployment and inflation rates which may impair social and political stability.

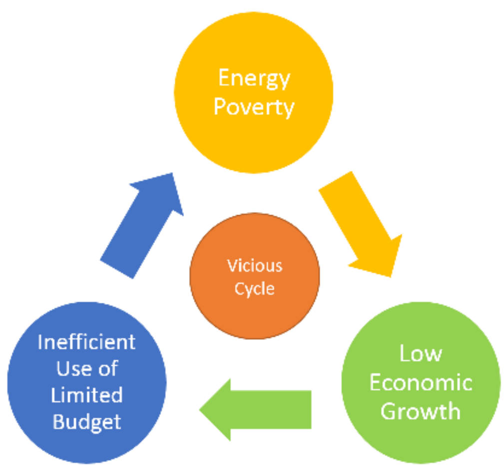

Figure 1: The Vicious Cycle of Energy-Economy (Rafique and Zhao 2011).

The case of Pakistan is exemplary. With the world's 5th largest coal reserves, Pakistan is suffering a severe electricity shortage in recent years. For instance, electricity shortages in summer 2013 amounted to 6,500 (MWh) with an estimated total demand of 16,500 (MWh). As reported by National Electric Power Regulatory Authority (NEPRA) of Pakistan, load shedding is as common as 9-12 hours a day in major cities. The energy deficiency puts many industrial sectors of Pakistan on the verge of collapse. For example, the output of textile and fertilizer sectors has fallen by nearly 40%-50%, which, gave rise

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to a sharp increase in unemployment rate due to the closure of hundreds of industrial units across the country (Santana 2013). It is estimated that electricity shortages have resulted an approximate cost of around 2-4% of GDP annually in the past few years.

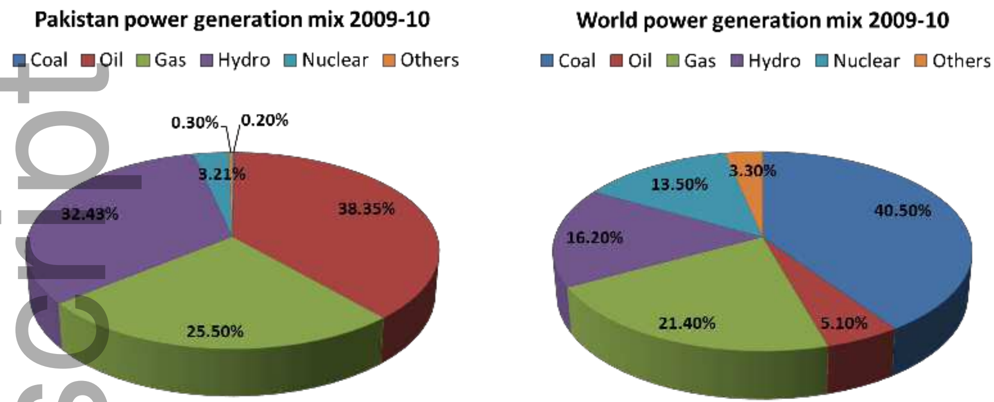

Figure 2: Energy Mix: Pakistan vs. World. Source: IEA 2011 and NEPRA 2011.

To resolve the energy deficiency, Pakistan has to rely heavily on imported oil which contributed 38.35% to the energy mix (Figure 2), in sharp contrast to the 5% world's average of electricity generation through oil (IEA 2011 and NEPRA 2011). Oil prices are higher and more volatile than those of coal, and thus the heavy dependence on imported oil puts Pakistan in a risky and pricey situation for power generation. As expected, electricity price has increased drastically in Pakistan together with the prices of numerous products and services that require electricity. The high inflation and unemployment rates combined are pushing millions of Pakistanis into poverty and riots. As reported by Kugelman (2013) in February 2013, Federal Minister for Water and Power in Pakistan warned that the energy crisis has become a national security issue.

As described by Malik (2008), the current energy mix is not sustainable for Pakistan with a fast growing population of 180 million and a fast growing economy with a real GDP of $133 billion in 2011. Pakistan is in urgent need of an inexpensive and reliable source for its future energy security and economic prosperity. Fortunately, the country has one of the world's largest coal reserves with approximately 185 billion tons of coal, equivalent to about 300 billion barrels of oil, exceeding the combined oil reserves of Saudi Arabia and Iran. Pakistan's coal, however, is nearly untapped. By IEA (2011), the world's average of electricity generation from coal is 41% but in Pakistan, coal made only a negligible 0.2% contribution to the total energy supplied (Figure 2). Although increasing the reliance on coal for power generation seems the option for the long-term energy security of Pakistan (Malik 2010), building up a coal-fired energy supply system from scratch presents a significant financial challenge especially given

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the country's heavy debts (Public debt 2012: 50.4% of GDP) and poor credit ratings (Standard and Poor 2012: B-, domestic; B-, foreign). What Pakistan can afford is a limited public fund each year.

In this paper, we apply supply chain design and location optimization models to the energy sector of developing countries to mitigate the predicament of "resource rich, energy poor". To turn the vicious energy-economy cycle into a prosperous cycle, we develop models, solutions and insights to effectively utilize the limited funds in building up a coal-fired energy supply chain for energy security and economic prosperity. Although meeting the basic need of energy access is the top priority, it is also desirable to be environmentally friendly.

1.2 Coal-Fired Energy Supply Chain

A coal-fired energy supply system can be viewed as an energy supply chain with the following major parts (tiers): coal reserves/mines, railway networks, power plants (PPs), transmission networks and demand zones (see Figure 3). Coal is exploited by mining the reserves, and transported via railway networks to power plants, where power (electricity) is generated and transmitted (distributed) by transmission networks to demand zones.

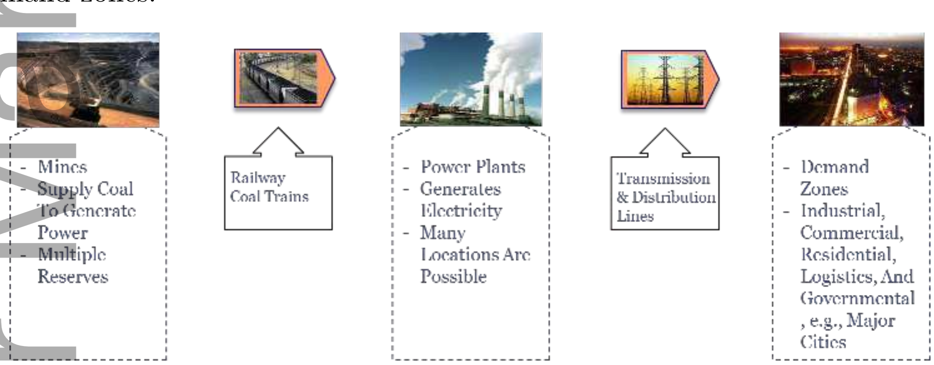

Figure 3: Coal-fired energy supply chains.

The supply chain view offers multiple advantages in designing energy supply systems. First, it emphasizes the end-to-end perspective from sourcing (mining) to production (power generation) and to distribution (transmission). Thus it provides a holistic view of the interacting parts in the system and an integrated approach for global optimization. Second, the supply chain view brings in the dynamic perspective needed in modeling the energy-economy cycle. Finally, the supply chain design literature offers powerful tools and methodologies to solve large-scale problems.

Despite the network analogy, an energy supply chain has unique features and economics that distinguish it from material supply chains (i.e., logistics networks).

1. A material supply chain deals with production, distribution and transportation of physical goods which can generally be stored. In contrast, a large part of an energy supply chain deals with the

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generation and transmission of power which can hardly be stored at a large scale. Thus an energy supply chain needs to be designed to meet the peak load.

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

3. Coal reserves are not renewable and may run out. However, factories and warehouses in a material supply chain can be rebuilt and run for an indefinite time.

4. Energy consumption has a strong impact on the economy (especially for developing / undeveloped countries), which may affect the budget for energy system development and in turn energy consumption (the energy-economy cycle). This dynamic feedback loop is rarely studied in material supply chains.

An energy supply chain is an integrated system where decisions on one part may affect other parts. For example, if power plants (PPs) are placed nearer to mines but farther away from demand zones, railway cost for coal transportation will be lower but the yield loss will be higher and so more PPs must be built. Conversely, if PPs are placed nearer to demand zones, then yield loss will be lower but the railway cost will be higher. Thus, an effective design of energy supply chains requires a delicate balance between the inbound (coal-transportation related) and outbound (transmission-yield induced) costs (*the cost trade-off*). The cost trade-off implies the importance of power plant locations. In general, it is challenging to balance this trade-off effectively due to the complex networks of energy supply chains with geographically dispersed demand zones and reserves.

The design of energy supply chains is further complicated by the energy-economy cycle. A fast influx of new energy from an easy-to-explore but small reserve can quickly boost the economy and increase budget for further development, but it may soon run out and the investment can be wasteful. Conversely, a hard-to-explore but large mine may take a long time and cost a bundle to be ready but it can last for a long time. Thus we must trade-off between quick, inexpensive but temporary supplies and slow, expensive but long-lasting supplies (*the time trade-off*). The time trade-off implies the importance of reserve selection and makes the energy supply chain design problem dynamic.

For projects of such size and scope, politics is always involved. Political issues such as equity (or fairness, see Muzamil 2015) in resource allocation must be considered to ensure feasibility. Thus energy supply chains should be designed to be both effective and politically feasible (correct).

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Pakistan exemplifies the challenges in energy supply chain design. Pakistan has two provinces that contributed significantly to the country's economy: Punjab (the industrial center contributing 60% of GDP) in the north and Sindh (the commercial center contributing 20% of GDP) in the south (Figure 4). Punjab (Sindh) accounts for about 60% (20%, respectively) of the country's total power consumption. Geographically, major cities of these two provinces scatter across the entire country with a direct distance between Lahore (the capital city of Punjab) and Karachi (the capital city of Sindh) of about 800 miles.

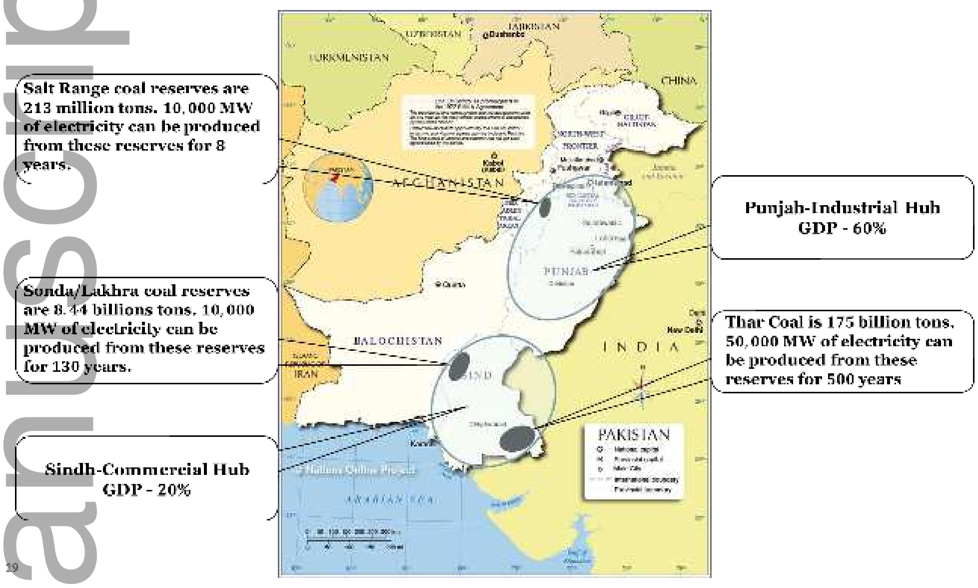

Figure 4: Pakistan coal reserves and major GDP provinces. Source: Sohail, et al. (2013).

Pakistan has three major coal reserves which account for about 98% of the country's total coal reserves (Figure 4): Thar, Sonda/Lakhra and Salt Range. Thar, the largest but least ready reserve, is located in the southeast corner of Pakistan, far away from all major demand zones. Salt Range, located in a close proximity to the largest demand zones in Punjab, is the smallest but most ready reserve. The medium reserve at Sonda/Lakhra is near the smaller demand zones in Sindh; its cost and readiness are in between those of Thar and Salt Range. The fact that the largest but least ready reserve (Thar) is closer to the smaller demand zones (Sindh) in the south and the smallest but most ready reserve (Salt Range) is closer to the largest demand zones (Punjab) in the north, makes the decisions of power plant location and mine selection in Pakistan intriguing, and the cost and time trade-offs hard to balance.

To save the railway costs and avoid investment on the smaller reserve(s) that may soon run out, Pakistan government's plan is to exploit the distant largest reserve at Thar and build all power plants nearby in Sindh. More than 800 miles of transmission lines are planned to transmit the power from Thar to Punjab and the rest of the country (Yusuf and Hasan 2015, Manan 2014). This plan is the result of a political conflict between Punjab and Sindh provinces for resources (Yusuf and Hasan 2015). Sindh

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won most of the development activities (and investment) largely because its plan (the government's plan) seems intuitive. However, the plan raises two concerns: (1) the accumulated yield loss of power transmission can be unbearable over a 800-mile distance. Despite savings from railway, one has to build more power plants to get the same output at Punjab. (2) The reserve at Thar requires the longest duration and heaviest investment to exploit.

While cost is an important factor, time is equally critical in designing energy supply chains. Giving the country's severe energy deficiency and collapsing economy, a timely supply of new energy will not only save Pakistan from bankruptcy but could also jump-start the economy, which in turn makes more budget available to the energy sector in the future. Hence, the exploitation of a nearby small reserve that may run out (like Salt Range) may not be wasteful because it is inexpensive and fast, and so can meet immediate needs. Of course, for such a strategy to work, one must design the energy supply chain strategically to facilitate an efficient transition from the small reserve to larger ones in the future.

To ensure equity and political feasibility, Pakistan government must consider the interests of Punjab and Sindh in the energy supply chain design. The government shall also account for its rapidly growing population and thus an increasing demand of energy at an average of 5-7% annually (Alter and Syed 2011, Iqbal, Nawaz and Anwar 2013).

1.3 Summary of Contributions

This paper contributes in the following ways:

- Modeling: We present a new class of supply chain design and location optimization models for developing countries to expand energy supply systems under limited public fund for energy security and economic prosperity. Incorporating the unique features and economics of energy systems in these countries, the models capture the cost trade-off (between inbound and outbound) in an integrated system from coal mining to power transmission, the time trade-off (induced by the energy-economy cycle) through an economy-dependent budget, and political equity issues associated with resource allocation. The resulting mathematic model is a multi-period mixed integer linear program (MILP) aiming at minimizing energy gaps (thus resolving "energy poor").

- Solutions and insights: The mathematical model produces solutions that are structurally different from the government's plan. In all scenarios, the first best solutions (from the model without political considerations) build power plants near demand zones and obtain coal supplies from close-by reserves. A tiered strategy is used for reserve exploitation which first explores the small nearby reserve in Punjab (in the north) then the medium and large reserves in Sindh (in the south). The politically best solutions (from the model with political considerations) attempt to balance the

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interests of the provinces by exploiting the reserves and building power plants in the south earlier than the first best. These solutions outperform the government's plan significantly by reducing the energy gaps much faster, boosting the economy much stronger with less greenhouse gas emissions. In an extensive sensitivity study, we demonstrate the impact of various system parameters on the solutions. Relating the results to practice, we provide insights on why the government's plan performs poorly, and how to build up an energy supply chain strategically for developing countries.

The rest of this paper is organized as follows: In Section 2, we review the related literature and elaborate our contributions. In Section 3, we present assumptions and justifications, the conceptual model, and the mathematical model in full detail. In Section 4, we apply the model to the real-life example of Pakistan to demonstrate the effectiveness of the solutions and to develop insights. Section 5 concludes this paper.

2 Literature Review

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

2.1 Design of Material Supply Chains

Facility location plays a critical role in the strategic design of logistics networks and supply chains for physical goods. The key questions answered by the literature include where to locate plants, warehouses and other facilities, and how to source supplies and serve customers either for a single period or over multiple periods.

The single-period (or static) logistics network design literature provides useful techniques and methodologies for modeling and solutions. Owen and Daskin (1998) reviews the fundamental models of location theory. Geoffrion and Graves (1974) studies the optimal location of intermediate distribution facilities between plants and customers. A multi-commodity capacitated single-period version of this problem is formulated as a mixed integer linear program and solved by Benders Decomposition. Shen, Coullard and Daskin (2003) studies a joint location-inventory problem where some retailers can serve as distribution centers to achieve risk pooling effect. The problem is formulated as a set-covering integer-programming model and solved by column generation algorithms. We refer the reader to Daskin, Snyder and Berger (2005), Snyder (2006) and Shen (2007) for literature reviews. In contrast to static models, the interaction between energy consumption and economy over time and the non-renewable reserves (see §1.2) make energy supply chains inherently dynamic.

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Dynamic models of logistics network design consider changing demand and/or cost, and relocation of facilities over multiple periods - features shared by energy supply chains. Wesolowsky (1973) studies the single facility location problem that permits location changes for a multi-period planning horizon. An algorithm is developed to optimize the sequence of locations in order to meet changes in cost, volume and location of destinations. Wesolowsky and Truscott (1975) extends this model to locate multiple facilities among many possible sites to serve different demand zones. Van Roy and Erlenkotter (1982) solves a capacitated dynamic location problem with opening and closing decisions using a dual-based branch-and-bound procedure. Drezner (1995) studies the "progress p-Median problem" which locates multiple facilities over time to meet changing demand in the minimum transport cost. We refer the readers to Owen and Daskin (1998) for a literature review, and Shapiro (2007) for applications of location models in material supply chains.

The dynamic facility location literature also considers budget limit, which is an important feature of energy supply chains. Eiselt and Marianov (2011) provides a review of the basic budget constrained location models. Melachrinoudis and Min (2000) considers the relocation and phase-out of a combined production and warehousing facility and provides a dynamic, multi-objective, mixed-integer programming model under budget constraints. Melo, Nickel and da Gama (2005) studies the gradual relocation of facilities over time for supply chains facing a limited budget, and develops a mathematical model for strategic supply chain design. We refer to Melo, et al. (2009) for a literature review.

Dynamic logistics network design models have been applied to industries of perishable products (food, high tech, etc.) where deterioration (loss) is an important feature. For instance, Hasani, Zegordi and Nikbakhsh (2012) studies a close-loop supply chain design problem for perishable goods with limited shelf-life and time dependent price. To handle uncertain demand and cost parameters, the paper provides a robust optimization model to make location, production, transportation, and reverse logistics decisions over multiple periods. The yield loss over distance in energy supply chains (see §1.2) differs from deterioration over time (finite shelf-life) of perishable products. While the latter imposes a time constraint on the storage of goods, the former, together with the non-storable property of power, gives rise to a cost trade-off in energy supply chains (§1.2) that connects the decisions of reserve selection, power plant locations, and rail/power line linkages.

The dynamic models for logistics network design cannot be directly applied to energy supply chains in developing counties because of the latter's unique features, economics and trade-offs (§1.2). Specifically, the yield loss and non-storable property of power (differences 1 and 2 in §1.2) lead to a different cost trade-off between inbound and outbound activities from a logistics network. In addition, the interaction between energy consumption and economy (difference 4 in §1.2) endogenizes the budget (in contract

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to exogenous budget often assumed in the logistics network design literature) and introduces a time trade-off that could play a significant role in system design and planning. Thus the design of energy supply chains in developing countries requires new models, solutions and insights.

2.2 Energy Economics and Policy

The energy policy and economics literature considers the specific features of an energy supply chain. Such studies are either empirical or analytical with some focusing on individual parts of an energy supply chain while others on energy system planning.

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

Mathematical models are developed in the energy economics and policy literature for power plant operations and locations related to solar, nuclear, wind and thermal sources. For instance, 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. 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 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

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multi-period planning model to optimize and expand power transmission system in India with growing demand for electricity. 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.

Studies that dealt with the planning of integrated energy systems include, most notably, the MARKAL family models, with the objective of minimizing the total cost of providing energy from various generating technologies to meet the demand of diverse industry sectors of a country/region. The MARKAL-MACRO model further integrates energy system planning with macro-economics through price-dependent demand and energy cost. We refer the reader to Connolly, Lund, Mathiesen and Leahy (2010) for a thorough review. Another class of models considers capacity expansion of energy systems in a geographic region where location and volume are important decisions. Mai, et al. (2013) provides a review on such models and presents a model with a high spatio-temporal resolution and a detailed representation of power dispatch. The model considers transmission yield but not coal transportation issues. These models typically do not consider limited budget with the exception of Kuby, et al. (1993) which provides a strategic planning model for China's thermal, hydro and nuclear power generations and electricity delivery system under exogenous budgets.

As pointed out by Urban, Benders and Moll (2007) and Bhattacharyya and Timilsina (2010), most of the current literature is devoted to developed countries, which may not be adequate for developing countries with different issues and objectives. This is especially true for those facing severe energy deficiencies where energy consumption is a strong driver for economic growth but the energy infrastructure is barely established. In these countries, the government often has to take a leading role in the development using public funds which depend on the economy. In comparison, the energy systems of developed countries are well established and it is often the market (not government) that drives development. Thus, their goals of energy system design are often cost efficiency, flexibility and/or environmental impact but not energy security.

Our work contributes to the literature by providing a new class of mathematical models for energy system planning for developing countries with severe energy deficits and yield losses. The model extends the supply chain design literature to capture both the cost and time trade-offs in the energy supply chains of these countries.

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3 Model Development

In this section, we establish the modeling framework on coal-fired energy supply chain from mining to transmitting power. Taking the perspective of the governments in developing countries, the **objective** of the model is to ensure energy security for the country by making appropriate decisions on reserve selection, power plant locations, coal supply and power distribution. We shall first make assumptions and justify them by practices and standards in the energy sector (§3.1), then provide a conceptual modeling framework (§3.2), and finally present the mathematical model in full detail (§3.3).

3.1 Assumptions and Justifications

Figure 5 provides an overview of the energy network structure.

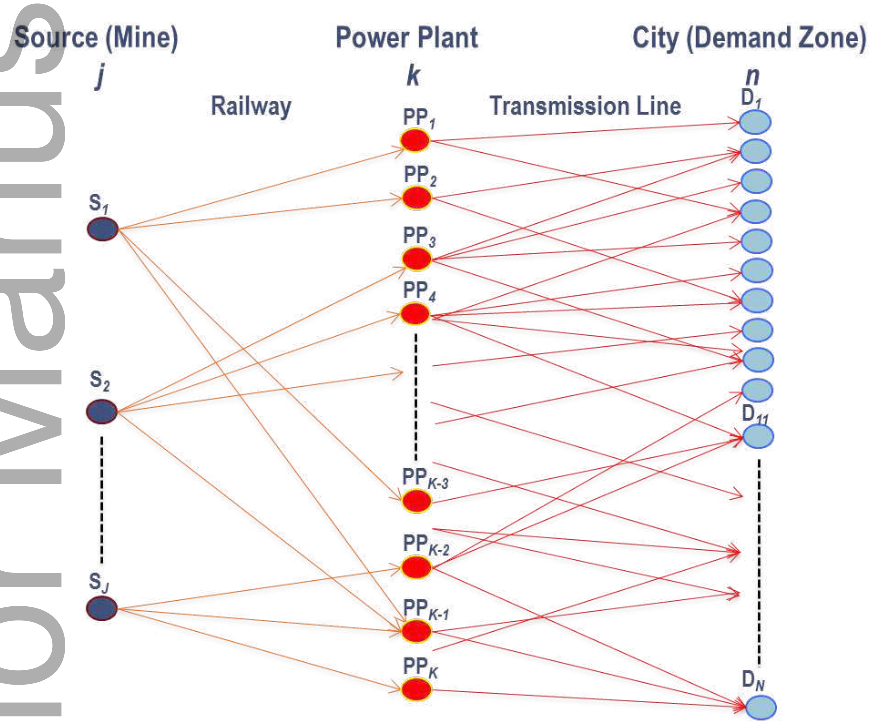

Figure 5: A Conceptual Model: Coal-fired Energy Supply Chain.

A coal-fired energy supply chain is a network of three echelons: coal reserves, power plants and demand zones. The coal reserves (upper-most echelon) are mined and coal is transported by freight trains via railway to the power plants (middle echelon), where the coal is burnt and the generated electricity is transmitted by power lines to the demand zones (lowest echelon). The actors of this supply chain are typically mining companies for reserve exploitation, rail services companies for coal transportation, power generation companies, and transmission/distribution companies (Rafique and Zhao 2011 provides examples for Pakistan).

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

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

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

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

3. *The potential locations for power plants include all reserves and demand zones which are indexed by* k *where* $k = 1, 2, ..., K$. *Although there is no limit on the number of power plants that can be built at the reserves, there are limits at demand zones (cities) due to environmental concerns.*

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

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

6. *All power plants have a capacity of* IC^{PP} *MWh and operate at full capacity with a daily consumption of coal of* DU^{PP} *tons.*

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

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

9. *The yield of transmission lines is* ω *for every 100 miles (hence the loss is* $1 - \omega$*).*

10. *The area/country consists of multiple political regions as indexed by* l *where* $l = 1, 2, ..., L$. *The potential locations of power plants* $\mathcal{K} = \{1, 2, ..., K\} = \mathcal{K}_1 \cup \mathcal{K}_2 \cup \ldots \cup \mathcal{K}_L$ *where* $\mathcal{K}_l \neq \emptyset$ *is the set of power plant locations in political region* l.

The first two assumptions in Assumption 1 are sufficiently general to cover real-life situations in Pakistan as well as other developing countries around the world. The third assumption is based on Rafique and Zhao (2011) which provides a thorough case study of the energy crises in Pakistan. This

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assumption does not lose generality as we can always include potential locations for power plants as demand zones. The limitations on the number of power plants are based on pollution and environment concerns (Chen and Xu 2010). The fourth and fifth assumptions are based on the common industry practice (Rosnes and Vennemo 2012, Bowen et al. 2010). The sixth assumption can be justified by standards in practice (Susta 2008). The seventh assumption can be justified by the heavy load required by power plants. The eighth assumption comes from the facts that reserves are likely unexplored in many developing countries and thus have no transmission infrastructure available, whereas in the demand zones, such infrastructure may be established and thus only an upgrade is needed to deliver a higher volume. The ninth assumption is justified in Section 1.2. The last assumption allows us to take political issues among different regions into consideration.

We shall consider a planning horizon of multiple periods (years), and make the following "regularity" assumptions:

Assumption 2 *Regularity assumptions:*

1. *The ration of budget allocated to coal-fired energy infrastructure development is RA percent of the real annual GDP (we use real GDP rather than nominal GDP to eliminate the impact of inflation).*
2. *Energy consumption has a significant impact on the real GDP.*
3. *Once we start construction or updating an energy infrastructure, we must complete the job without preemption.*
4. *Power sources other than coal run as BAU (business as usual).*

We define the budget as a percentage of the real GDP (the first assumption in Assumption 2) because of the government's funding allocation practice (Federal Budget Publications of Pakistan 2014-15). In each year, a certain percentage of the public fund is allocated to the energy sector, where the available fund depends on the GDP, and the percentage depends on competing priorities and has to be decided by the government. The second assumption is justified by the energy economics literature (§2.2) and our empirical study of Pakistan's data (§4). We make the third assumption for convenience because of the unpredictable political circumstances in the planning horizon. We make the fourth assumption in order to focus on coal.

3.2 The Conceptual Framework

In this section, we present a conceptual framework to outline the structure of the mathematical model and show intuitively how different parts are connected and interacting.

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The model is designed for the governments of developing countries to minimize the total discounted energy gap among all demand zones over a given planning horizon. Energy gap is defined as the unmet demand, that is, the projected or targeted (by the government) energy consumption (based on peak load) less demand already met, and thus is exogenous. For developing countries facing severe energy deficiencies, the energy gap is directly linked to a broad range of issues such as economic development, unemployment, political stability and national security. Thus, energy gap is one measure that can reflect, broadly, these countries' economic and societal priorities. The discounted factors serve to normalize and discount the penalties of the energy gaps over time.

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

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

1. **Mine constraints**: Reserves have limited supplies.
2. **Railway constraints**: Railway and train have capacity limits.
3. **Power plant constraints**: A limited number of power plants can be built in each potential location.
4. **Network constraints**: A power plant's electricity output is constrained by its input of coal and generating capacity.
5. **Demand and transmission constraints**: The system can't supply more electricity than what is needed at each demand zone.
6. **Budget constraints**: The budget is a fraction of the GDP which depends on energy consumption.
7. **Political constraints**: The allocation of the budget to regions must be fair, e.g., no region can get an excessive share.

While many of these constraints come from capacity limits at various parts of the supply chain, we should point out that the network constraint connects coal supply with power generation and transmission, and thus is critical for the model to capture the cost trade-off between fuel-transportation and yield-loss. The budget constraint provides a feedback loop from energy consumption to GDP, and in turn to the available budget for further development of energy infrastructure. The political constraints

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ensure equity in budget allocation for local development - an issue that different regions fight for (Muzamil 2015). The optimal solution obtained without these political constraints presents a centralized "first best" solution which serves as a benchmark for the government. The optimal solution satisfying these constraints presents a "politically best" (the best politically feasible) solution.

To solve this problem, we shall construct a mixed integer and linear programming model (MILP) to optimally balance the cost and time trade-offs on the energy supply network. Indeed, even for a simple system with only two reserves, two energy demand zones and a number of potential power plant locations, a numerical calculation is needed to evaluate each combination of power plant location and reserve selection because of the discrete decisions, location specific costs and the dynamic nature of the problem.

3.3 Mathematical Model

In this section, we present the mathematical model for the optimal design of coal-fired energy supply chains. We define indices in Table 1, which is followed by decision variables in Table 2 and intermediate variables in Table 3. All decision variables are non-negative.

Index	Name	Set
j	Mines (reserves)	$\{1, 2, ..., J\}$
k	Power plant locations	$\{1, 2, ..., K\}$
n	Demand zones	$\{1, 2, ..., N\}$
l	Political regions	$\{1, 2, ..., L\}$
t	Time	$\{1, 2, ..., T\}$

Table 1: Indices.

.

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

Table 2: Decision Variables.

3.3.1 Objective Function

Let G_{nt} be the forecasted energy gap at demand zone n in year t (in MWh), D_{kn} be the distance between power plant location k and demand zone n (in 100 miles), and β_t be a series of time discounted factors

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decreasing in t, then the objective function, i.e., the total discounted energy gap for all demand zones over a finite planning horizon T, is,

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

where ω is the yield of power transmission every 100 miles, and the second term in the parenthesis represents the total energy consumed at demand zone n in year t.

Mines			
b_t^{CM1}	Cost of setting up the mines in year t	Continuous	Unit: \$1,000
b_t^{CM2}	Cost of operating the mines in year t	Continuous	Unit: \$1,000
Railway			
b_t^{RW1}	Cost of setting up railways in year t	Continuous	Unit: \$1,000
b_t^{RW2}	Cost of operating railways in year t	Continuous	Unit: \$1,000
b_t^{TR}	Cost of purchasing trains in year t	Continuous	Unit: \$1,000
Power Plants / Power Supplies			
b_t^{PP1}	Cost of building power plants in year t	Continuous	Unit: \$1,000
b_t^{PP2}	Cost of building grid stations and operations in year t	Continuous	Unit: \$1,000
Other Variables			
g_t	GDP in year t	Continuous	Unit: \$1,000

Table 3: Intermediate Variables.

3.3.2 Mine Constraints

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

$$\sum_{k=1}^{K}\sum_{\tau=1}^{t} q_{jk\tau} \leq CR_j \cdot \sum_{\tau=1}^{t} w_{j\tau} \qquad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad t = 1, \ldots, T, \tag{2}$$

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

The second set of constraints for mines specifies their availability. Because a mine can only be setup once, thus

$$\sum_{t=1}^{T} w_{jt} \leq 1 \qquad \text{for} \quad j = 1, \ldots, J. \tag{3}$$

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

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

$$b_{jt}^{CM1} = I_j^{CM} \cdot \sum_{\tau=t+1}^{t+T_j^{CM}} w_{j\tau} \qquad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad t = 1, \ldots, T - T_j^{CM}, \tag{4}$$

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

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

$$b_{jt}^{CM1} = I_j^{CM} \cdot \sum_{\tau=t+1}^{T} w_{j\tau} \qquad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad t = T - T_j^{CM} + 1, ..., T-1, \tag{5}$$

and

$$b_{jT}^{CM1} = 0 \qquad \text{for} \quad j = 1, \ldots, J. \tag{6}$$

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

$$b_t^{CM2} = OC^{CM} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} q_{jkt} \qquad \text{for} \quad t = 1, \ldots, T, \tag{7}$$

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

3.3.3 Railway Constraints

We shall only consider railway upgrading in this section. New railway construction uses the same equations but with different cost and time parameters. The first set of constraints specifies the availability of the railway. Let D_{jk} be the distance between mine j and power plant location k (in 100 *miles*) and M be a large number. Note that x_{jkt} is the indicator on the availability of the railway between j and k in year t, and nt_{jkt} is an integer variable representing new coal trains purchased on this railway (Table 2), then

$$\sum_{t=1}^{T} x_{jkt} \leq 1 \qquad \text{where} \quad D_{jk} > 0, \quad \text{for} \quad j = 1, \ldots, J \quad \text{and} \quad k = 1, \ldots, K. \tag{8}$$

Constraint 8 ensures that the railway between mine j and power plant location k is set up only once.

$$q_{jkt} \leq CR_j \cdot \sum_{\tau=1}^{t} x_{jk\tau} \qquad \text{where} \quad D_{jk} > 0, \quad \text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{9}$$

Constraint 9 indicates that coal can only be transported if the corresponding railway is set up.

$$nt_{jkt} \leq M \cdot \sum_{\tau=1}^{t} x_{jk\tau} \qquad \text{where} \quad D_{jk} > 0, \quad \text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{10}$$

Constraint 10 connects trains to the availability of railway. Because a railway takes multiple years to setup, we have the following initial conditions: $x_{jkt} = 0$ for $t = 1, 2, ..., T^{RW}$ where T^{RW} is the railway setup time.

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The second set of constraints is on railway capacity which depends on the frequency and capacity of trains. Let RT_{jk} be the round trip time between j and k (in *hour*), then Constraint 11 specifies an upper limit on the number of trains between j and k.

$$\sum_{\tau=1}^{t} nt_{jk\tau} \leq BF^{TR} \cdot RT_{jk} \qquad \text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T, \tag{11}$$

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

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

$$q_{jkt} \leq C_{jk}^{TR} \cdot \sum_{\tau=1}^{t} nt_{jk\tau} \qquad \text{where} \quad D_{jk} > 0, \quad \text{for} \quad j = 1, \ldots, J, \quad k = 1, \ldots, K \quad \text{and} \quad t = 1, \ldots, T. \tag{12}$$

Constraint 12 specifies the maximum railway capacity based on train capacity and frequency.

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

$$b_t^{RW1} = \sum_{j=1}^{J} \sum_{k=1}^{K} (\frac{SC_{jk}^{RW}}{T^{RW}} \cdot \sum_{\tau=t+1}^{t+T^{RW}} x_{jk\tau}) \qquad \text{for} \quad t = 1, \ldots, T - T^{RW}, \tag{13}$$

$$b_t^{RW2} = OC^{RW} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} (D_{jk} \cdot q_{jkt}) \qquad \text{for} \quad t = 1, \ldots, T, \tag{14}$$

$$b_t^{TR} = I^{TR} \cdot \sum_{j=1}^{J} \sum_{k=1}^{K} nt_{jkt} \qquad \text{for} \quad t = 1, \ldots, T, \tag{15}$$

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

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

$$b_t^{RW1} = \sum_{j=1}^{J} \sum_{k=1}^{K} (\frac{SC_{jk}^{RW}}{T^{RW}} \cdot \sum_{\tau=t+1}^{T} x_{jk\tau}) \qquad \text{for} \quad t = T - T^{RW} + 1, ..., T - 1, \tag{16}$$

$$b_T^{RW1} = 0. \tag{17}$$

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3.3.4 Network Constraints

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

$$e_{kt} \leq \frac{IC^{PP}}{DU^{PP} \cdot 365} \cdot \sum_{j=1}^{J} q_{jkt} \qquad \text{for} \quad k = 1, \dots, K \quad \text{and} \quad t = 1, \dots, T, \tag{18}$$

where $\frac{IC^{PP}}{DU^{PP} \cdot 365}$ is the conversion rate between coal and power as 2000 tons of coal is needed every day for a power plant to maintain its full capacity at 300 MWh year around.

$$e_{kt} \leq IC^{PP} \cdot \sum_{\tau=1}^{t} y_{k\tau} \qquad \text{for} \quad k = 1, \dots, K \quad \text{and} \quad t = 1, \dots, T. \tag{19}$$

Constraint 19 limits the electricity generated by the power plant capacity.

$$\sum_{n=1}^{N} p_{knt} \leq e_{kt} \qquad \text{for} \quad k = 1, \dots, K \quad \text{and} \quad t = 1, \dots, T. \tag{20}$$

Constraint 20 ensures that the amount of electricity transmitted is less than electricity generated at each location.

3.3.5 Power Plant and Transmission Constraints

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

$$\sum_{\tau=1}^{t} y_{k\tau} \leq UB_k \qquad \text{for} \quad k = 1, \dots, K \quad \text{and} \quad t = 1, \dots, T. \tag{21}$$

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

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

$$b_{kt}^{PP1} = I^{PP} \cdot \sum_{\tau=t+1}^{t+T^{PP}} y_{k\tau} + SC_k^{TL} \cdot y_{kt} \qquad \text{for} \quad k = 1, \dots, K \quad \text{and} \quad t = 1, \dots, T - T^{PP}, \tag{22}$$

$$b_t^{PP2} = \sum_{k=1}^{K} OC^{PP} \cdot e_{kt} \qquad \text{for} \quad t = 1, \dots, T, \tag{23}$$

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

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

$$b_{kt}^{PP1} = I^{PP} \cdot \sum_{\tau=t+1}^{T} y_{k\tau} + SC_k^{TL} \cdot y_{kt} \qquad \text{for} \quad k = 1, \ldots, K \quad \text{and} \quad t = T - T^{PP} + 1, \ldots, T-1, \tag{24}$$

$$b_{kT}^{PP1} = 0. \tag{25}$$

3.3.6 Demand Constraints

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

$$\sum_{k=1}^{K} (\omega^{D_{kn}} \cdot p_{knt}) \leq G_{nt} \qquad \text{for} \quad n = 1, \ldots, N \quad \text{and} \quad t = 1, \ldots, T. \tag{26}$$

3.3.7 Budget and Political Constraints

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

$$\sum_{j=1}^{J} b_{jt}^{CM1} + b_t^{CM2} + b_t^{RW1} + b_t^{RW2} + b_t^{TR} + \sum_{k=1}^{K} b_{kt}^{PP1} + b_t^{PP2} \leq g_{t-1} \cdot RA_t \qquad \text{for} \quad t = 1, \ldots, T, \tag{27}$$

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

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

$$g_1 = g_0 + Coef \cdot \sum_{k=1}^{K} \sum_{n=1}^{N} (\omega^{D_{kn}} \cdot p_{kn1}), \tag{28}$$

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

$$g_t = g_{t-1} + Coef \cdot \sum_{k=1}^{K} \sum_{n=1}^{N} \{\omega^{D_{kn}} \cdot (p_{knt} - p_{knt-1})\} \qquad \text{for} \quad t = 2, \ldots, T. \tag{29}$$

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

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The political constraints specify the share of the budget that each region cannot exceed. These constraints represent the typical practice of the government to balance the economic development of different regions. We assume that such constraints only apply to capital investment on the reserves, power plants and grid stations, but neither to operating costs nor to the capital investment on railways and transmission lines (as they connect different regions). Let α_{lt} be the share of the budget on these capital investments that region l in year t is entitled to at most, then,

$$\sum_{j \in \mathcal{K}_l} b_{jt}^{CM1} + \sum_{k \in \mathcal{K}_l} b_{kt}^{PP1} \leq \alpha_{lt} \cdot g_{t-1} \cdot RA_t \qquad \text{for} \quad l = 1, \ldots, L \quad \text{and} \quad t = 1, \ldots, T. \tag{30}$$

4 Numerical Study

In this section, we apply the mathematical model to Pakistan to demonstrate its potential impact and to develop insights. Section 4.1 presents the real-life situations of Pakistan, and Section 4.2 provides solutions and insights.

4.1 The Case of Pakistan

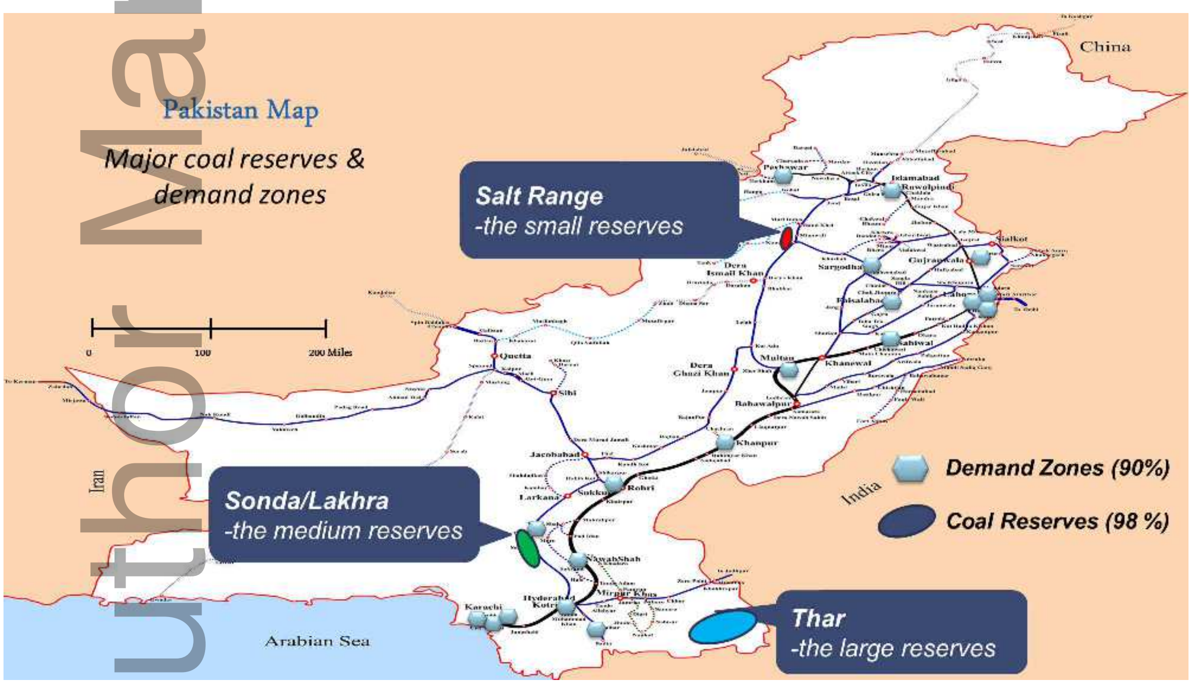

Figure 6: Pakistan map with major coal reserves and demand zones. Modified from "Pakistan Railway Network Map" by Adnanrail, Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons.

A map of Pakistan coal reserves and major demand zones is shown in Figure 6.

A thorough case study of Pakistan's energy crises by Rafique and Zhao (2011) provides the following observations.

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

1. *Three largest coal reserves (Figure 6): Thar, Sonda/Lakhra and Salt Range, account for 98% of Pakistan's total coal reserves,* $J = 3$. *The reserves that are of sufficient quality for power generation are listed in Table 4. As we can see, Thar and Sonda/Lakhra reserves have ample reserves to meet demand in any reasonable planning horizon but Salt Range does not.*

2. *There are 19 demand zones that account for 90% of the country's total energy consumption (Figure 6),* $N = 19$. *14 of them are major energy-consumption cities and 5 of them are smaller cities but ideal locations for power plants. Demand for energy is estimated to grow at a rate of 5-7% annually (Section 1.2).*

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

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

5. *There are two political regions, Punjab and Sindh provinces, so* $L = 2$. *There are 12 PP locations (including Salt Range) in Punjab and 10 PP locations (including Sonda/Lakhra and Thar) in Sindh.*

We consider planning horizons of 15 and 20 years ($T = 15, 20$) as typical in the literature (see, e.g., Kuby, et al. 1993).

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

Table 4: Pakistan Coal Reserves. Source: Rafique and Zhao (2011).

Table 5 specifies the model parameters for Pakistan. Note that the mine setup costs, I_j^{CM}, include water supply related costs. The matrices of D_{jk} and D_{kn} are determined by the geology and transportation network of Pakistan. $RT_{jk} = 2D_{jk}/0.5 + LT + UT$ where 0.5 refers to the average train speed of 50 miles/hour, and LT (UT) refers to loading (unloading, respectively) time. $F_{jk} = 24/RT_{jk} \cdot 365$ where the numbers 24 and 365 refer to 24 hours a day and 365 days a year respectively. G_{nt} depends on the demand of the starting year and the projected growth rate. The cost matrix of railway, SC_{jk}^{RW},

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is calculated by the distance matrix D_{jk} and a setup cost of \$0.73 million/mile for upgrading (or \$13 million/mile for new construction) (Ministry of Pakistan Railway). The setup cost of transmission and grid station for a new power plant, SC_k^{TL}, is calculated by the distance from location k to the nearest grid station and a transmission line cost of \$1.8 million/mile for new (or \$0.6 million/mile for upgrading) as well as a local grid station cost of \$33,000/ MWh (these are best estimates on average based on data from Pakistan government and the worldwide industry standard by Electric Power Research Institute 2005). All power plants use the latest IGCC (integrated gasification combined cycle) technology with a capacity of 300 MWh and consume coal at a rate of $2,000$ ton daily (Susta 2008).

Currently, Pakistan only uses the alternating current (AC) technology for power transmission (National Transmission and Despatch Company 2014). Although the feasibility of the direct current (DC) technology is being studied in Pakistan (2014 Board of Investment Prime Minister's Office), it is expected that AC will remain the dominant form of long distance transmission in the next 10-15 years due to the high cost and risk of adopting a new technology (Weedy, et al. 2012). Pakistan's electricity is transmitted via 230kv and 500kv lines for which the yield losses per 100 miles are 6.9% and 1.5% respectively (Hurlbut 2012). For simplicity, we estimate, the weighted (by length) average yield loss per 100 miles, $(1-\omega)$, to be 4.5%.

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

Table 5: Parameters for Pakistan. Sources: Rafique and Zhao (2011).

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Our empirical study based on Pakistan's data from 1971 to 2011 (details omitted) confirms the impact of energy consumption on Pakistan's economy (see Shahbaz, Zeshan and Afza 2012, Tang and Shahbaz 2013). The impact of energy consumption on real GDP can be captured by a linear coefficient of Coef = 12,254. We select 2011 as the starting year ($t = 0$) with a GDP $g_0 = 133,000,000$ (in *\$1000*), a peak demand (summer peak load) of 15,000 MWh, and an energy gap of 6,000 MWh (Kessides 2013).

We choose RA to be 1%, 2%, ..., to 5% of real GDP because developing countries suffering from energy deficiency can only provide limited funding for energy system development. In Pakistan, the budgetary allocation to its energy sector in the last few years ranges from 10% to 15% (Federal Budget Publications 2014-15). However, most of the budget is spent on maintenance and operations of existing infrastructures. Only a small amount is dedicated to new ventures. Thus any budget allocation of a higher than 5% of GDP to the new energy projects may be unrealistic.

Because capital investment on reserves, power plants and grid stations is constantly around 82% of the total budget in the first best solutions, we set α_{1t} (α_{2t}) in Eq. (30) to be 82% multiplied by the shares of capital budget for Punjab (Sindh): 80%(20%), 60%(40%), ..., 20%(80%); see Table 6.

RA	Budget ration	$1\%, 2\%, ..., 5\%$
T	Planning horizon	15 or 20 years
N/A	Projected demand growth rate	5% or 7%
$\alpha_{1t}(\alpha_{2t})$	Share of budget on capital investment for Punjab (Sindh)	$80\%(20\%), 60\%(40\%), ..., 20\%(80\%)$ of 82%

Table 6: Parameters for numerical studies.

4.2 Solutions, Impact and Insights

In this section, we present the optimal solutions (first best and politically best) generated by the mathematical models for Pakistan in various scenarios and compare them to the government's plan on metrics such as cost per MWh consumed (for cost efficiency), net GDP (GDP less investment, for economic growth), energy gap (for energy security), and coal efficiency (coal burnt annually per MWh consumed, for carbon footprint). We provide insights on how an energy supply chain should be built up strategically, why the government's plan may perform poorly, and how various system parameters affect the results.

To ensure fairness in comparison, we applied the same procedure to calculate the coal transportation plan and demand zone service plan (the operational decisions) in the optimal solutions and government's plan. Thus, the performance difference among them should come from strategic level decisions, such as power plant location and reserve selection.

The mathematical model leads to large-scale multi-period mixed integer programs. For example, the scenarios of 15-year planning horizon without the political constraints have 5,907 constraints, 1,808

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integer variables, 1,402 binary variables and 6,001 continuous 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 5.6. Due to the complexity of the model, an optimal solution is not always achievable. We accept suboptimal but best solutions found if the values of their objective functions are sufficiently close to those of the optimal solutions or a certain limit of running time is reached. For example, the median of the MIP gap (computing time) of the first best solutions in the first study is 0.98% (35.4 minutes) with a 75% quantile of 2.5% (61.6 minutes). All computations are done on a desktop computer with an Intel Xeon E5-2620 2.0 GHz and 20 GB RAM.

A Representative Example.

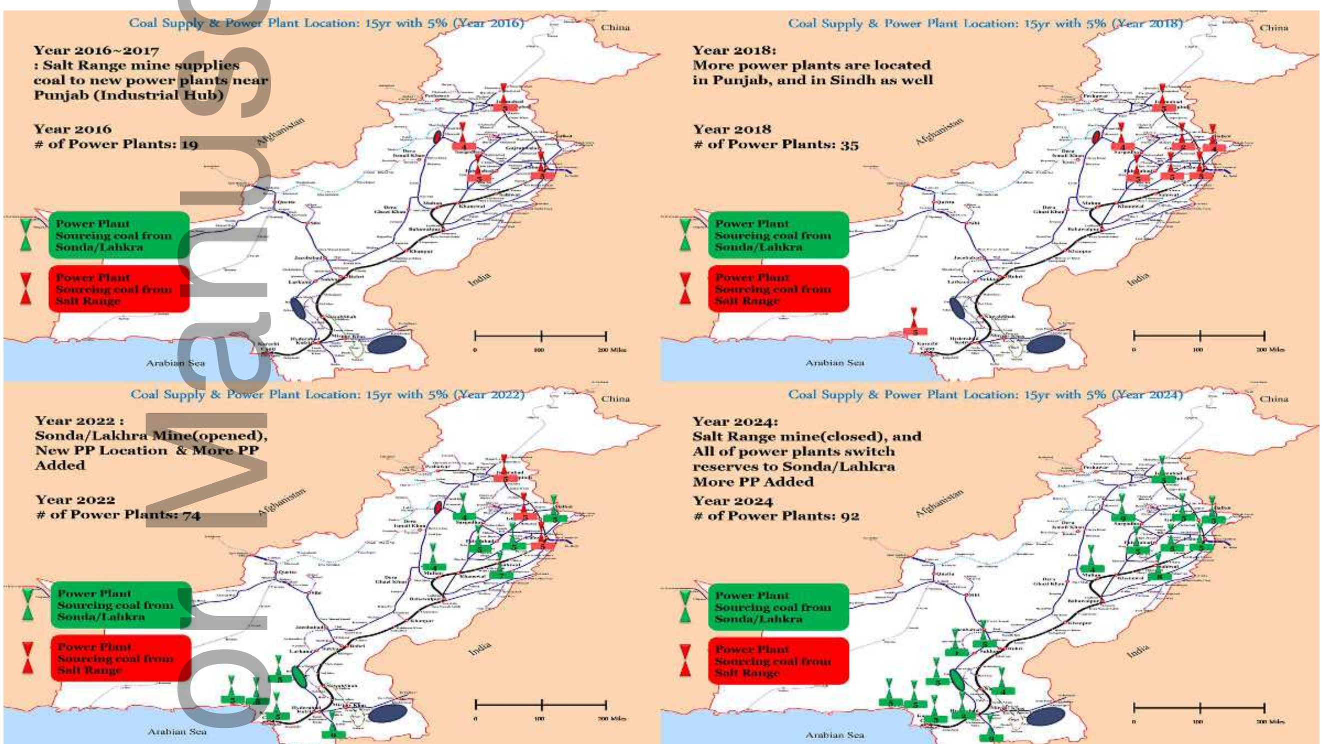

Figure 7: The optimal solution (first best) on reserve selection and power plant locations for the scenario with 7% demand growth, a budget of 5% GDP and a 15-year planning horizon. Circles - coal reserves; empty circles - reserves that run out; collate shapes - power plants (the box below indicates the number of power plants in service).

The mathematical model provides intriguing solutions, which are structurally different from the government's plan. Recall that the government's plan explores only the largest reserve at Thar and builds all power plants around that location. For comparison, let's consider a representative scenario with 7% demand growth, a budget of 5% of GDP and a planning horizon of 15 years (see Figure 7). The optimal solution (first best) first exploits the smallest reserve (Salt Range in the north) near the largest demand zones (the industrial hub in Punjab) that requires much less time and capital to setup

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than other reserves. The medium reserve at Sonda/Lakhra (in the south) near the commercial hub in Sindh is next exploited, but the largest reserve at Thar (in the southeast corner) is not setup for mining throughout the planning horizon in this scenario.

Power plants are first built close to the largest demand zones in Punjab and supplied locally by the Salt Range mine so as to minimize the yield loss at an affordable coal transportation cost. After the medium reserve at Sonda/Lakhra is setup, power plants are then built at demand zones in Sindh and supplied locally by the Sonda/Lakhra mine. When the Salt Range mine runs out (it depletes in about 12 years in this scenario), the power plants in Punjab shall switch supply from Salt Range to Sonda/Lakhra in Sindh. Power plants may be built at coal reserves after the demand zones run out of space.

Figure 8 illustrates how the optimal solution supplies demand zones and reduces energy gaps in this scenario. Electricity is first supplied to the demand zones in Punjab, and then to demand zones in Sindh. In about 10 years, the optimal solution reduces energy gaps at all demand zones to zero, and it remains so till the end of the planning horizon.

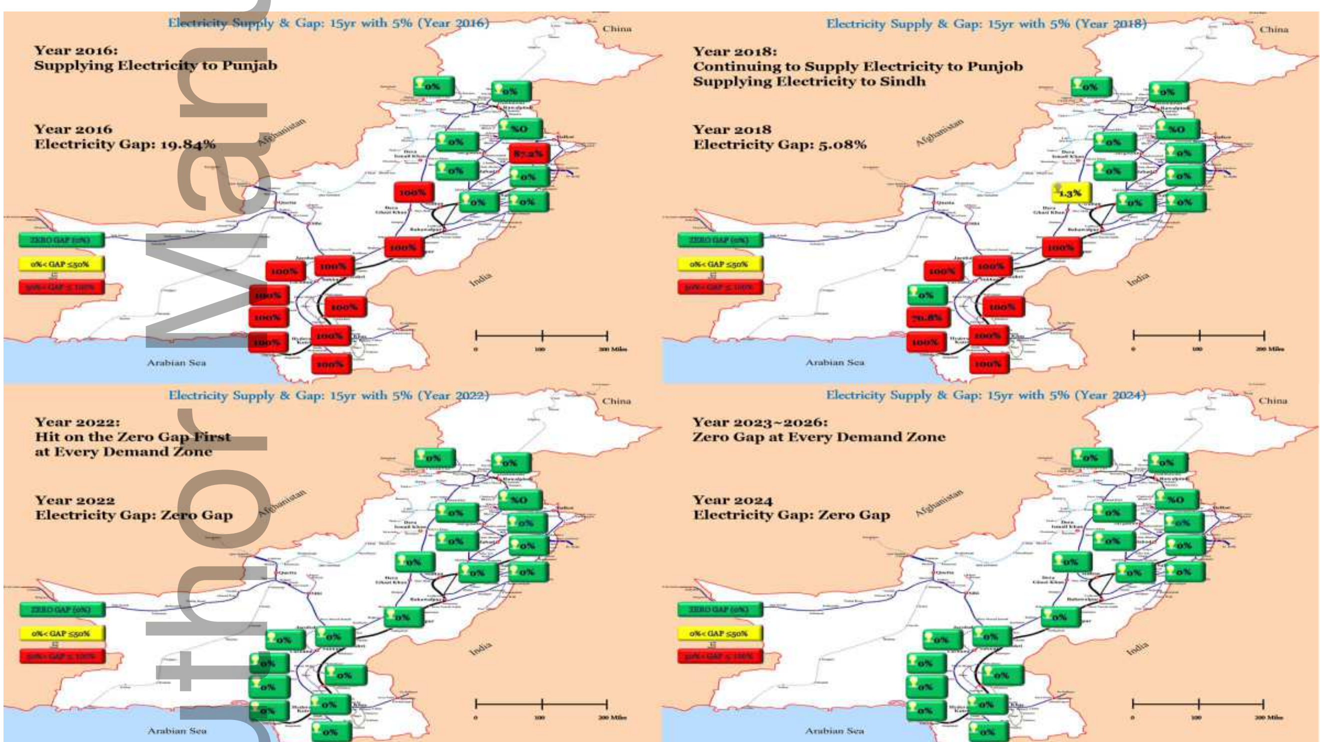

Figure 8: The optimal solution (first best) on transmission and energy gaps at demand zones for the scenario with 7% demand growth, a budget of 5% GDP and a 15-year planning horizon. Green - 0% gap, yellow - 1% to 50% gap, red - 51% gap and above.

The unique features of energy supply chains in developing countries play a critical role in shaping up the optimal solution. Specifically, power plants are first built at demand zones until the limit on the number of power plants is reached. This solution is driven by the *yield loss* as power plants are

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more expensive to build than railways. Despite the limited reserve at Salt Range, the optimal solution exploits it starting from the beginning because of the *dynamic interaction* between energy consumption and economy. Although Salt Range has the smallest reserve, it is inexpensive and fast, and also close to the largest demand zones. In contrast, Thar has the largest coal reserve but it is not only remote from all demand zones but also requires the highest investment and longest time to set up the mining infrastructure. Intuitively speaking, "distant ocean cannot put off a nearby fire." Although the Salt Range reserve does not last long, it can jump-start the energy supply, which in turn fuel the economy and lead to more funds to be invested back to the energy sector in the future (to explore, for instance, the Thar reserve). Doing so can help turning the vicious energy-economic cycle into a prosperity cycle. Thus the capital invested to exploit Salt Range is not a waste but a worthy investment.

In comparison, the politically best solution is obtained for the same scenario with a 60-40 split of the capital budget between Punjab and Sindh. This solution differs from the first best by exploiting the reserves in the south (e.g., Sonda/Lakhra) and building power plants at Sindh earlier than the first best.

To quantify the impact, we compare the first best and politically best solutions with the government's plan on four metrics (Figure 9): cost efficiency, i.e., cumulative cost over cumulative MWh consumed (a), net GDP (b), country-wide energy gap (c) and coal efficiency (d). As we can see, the first best solution significantly outperforms the government's plan by spending much less for each MWh consumed (Figure 9a), boosting the economy much stronger (Figure 9b), reducing the energy gaps much faster (Figure 9c) with less coal burnt per MWh consumed (Figure 9d). The optimal solution delivers much more electricity to the demand zones with a higher coal efficiency than the government's plan, and thus it is more sustainable. Specifically, the optimal solution can reduce the energy gap down to zero in about 10 years while the government's plan maintains an approximately 25% energy gap towards the end of planning horizon. Consequently, the optimal solution will generate a net GDP in the 15th year of $512 billion, as compared to $382 billion of the government's plan. Finally, for every MWh consumed, the first best solution may reduce the coal burnt in the government's plan by up to 16%.

The performance of the politically best solution lies in between the first best and the government's plan in all dimensions except coal efficiency. This is true because the politically best solution attempts to balance the economic development between Punjab and Sindh provinces but at a cost of the system efficiency. Despite a higher coal efficiency due to a better locally supplied coal, the politically best solution builds fewer PPs in Punjab to meet the need of this major demand zone, and thus is slower in reducing the total energy gaps and growing economy than the first best. This loss of efficiency in energy gap reduction and economic growth is the price paid for equity.

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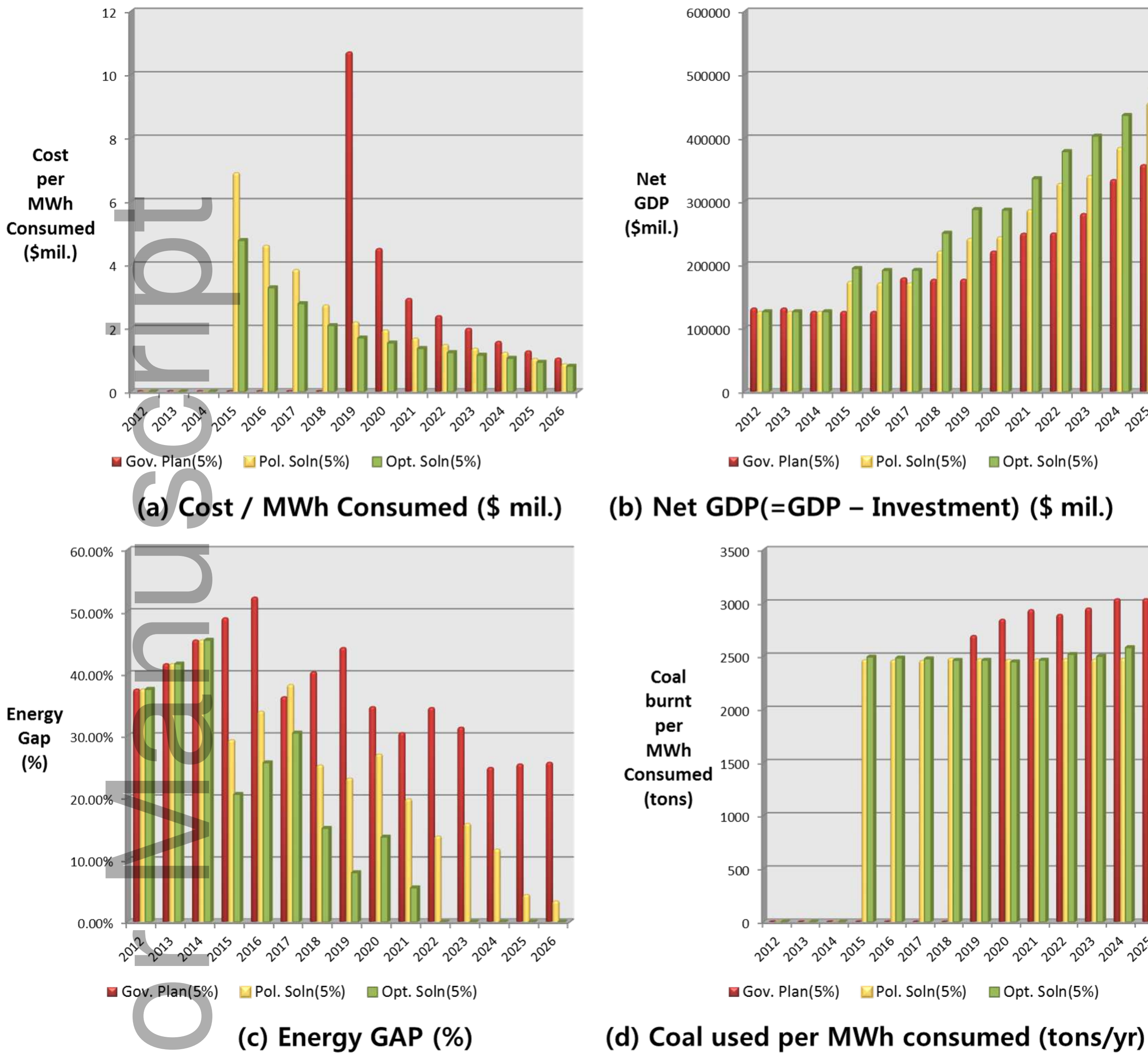

Figure 9: Optimal solution (first best) vs. Political Solution (politically best) vs. Government's plan. The x-axis is on time (in year). 7% demand growth, 5% ration and 15-year planning horizon.

Sensitivity Study

We now study the robustness of the solutions and the impact of various system parameters such as budget (ration), planning horizon, demand growth rate and the share of capital budget between Punjab and Sindh (see Table 6 for parameters). For all scenarios examined, the first best and politically best solutions stay qualitatively the same in the selection of reserves and PP location. The most notable difference between the scenario with 5% ration and those with less than 5% rations is that in the latter, one may not be able to reduce the energy gap to zero. In scenarios with 5% demand growth, the first

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best and politically best solutions may reduce energy gaps to zero much faster than the government's plan. Thus, our model can be used to justify the budget required to bring down the energy gap to zero in targeted years.

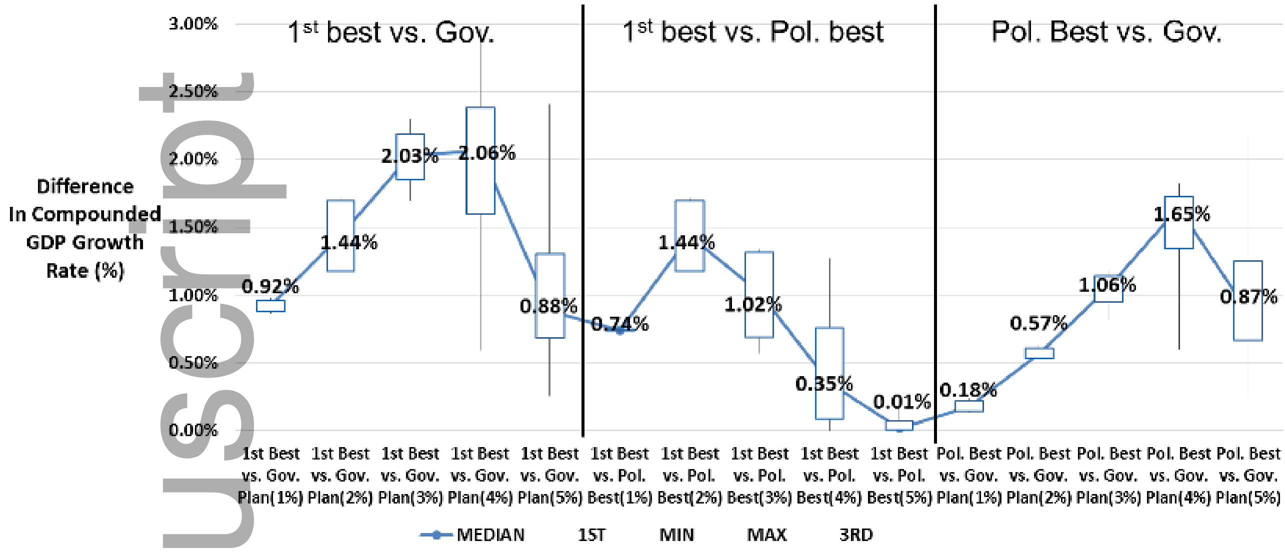

Figure 10: Boxplot of the difference in the compounded GDP growth rate among the first best, politically best and government's plan for various budget rations.

To study the impact of the budget ration, we box plot the differences in the compounded GDP growth rate among the first best, the politically best and the government's plan for each ration over all combinations of demand growth rates, planning horizons and budget shares (Figure 10). The figure shows that although the first best always outperforms the government's plan, it makes the greatest difference on the GDP growth rate when the budget is neither too tight nor too generous. This observation holds true also between the politically best and government's plan. Intuitively, if the budget is very tight, it allows little flexibility for the optimal solutions to improve; if the budget is very generous, cost efficiency as achieved by the optimal solutions becomes relatively unimportant as funding is abundant. The figure also shows that as budget increases, the politically best quickly approaches the first best in performance.

Our numerical study also shows (details omitted) that a longer planning horizon may reduce the performance gaps among the first best, the politically best and the government's plan. This is true because the energy gaps can be reduced to zero and stay this way for a longer time in a longer planning horizon under all approaches (especially for a large ration), during which time, the GDP growth rate is independent of the solutions.

To study the impact of demand growth rate, we box plot the differences in the compounded GDP growth rate among the first best, the politically best and the government's plan for each demand growth rate over all combinations of budget rations, planning horizons and budget shares (Figure 11). The

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figure shows that a large demand growth rate tends to statistically increase the performance gaps among the solutions and government's plan, which implies that the first best and the politically best solutions can generate more benefits for a higher demand growth rate.

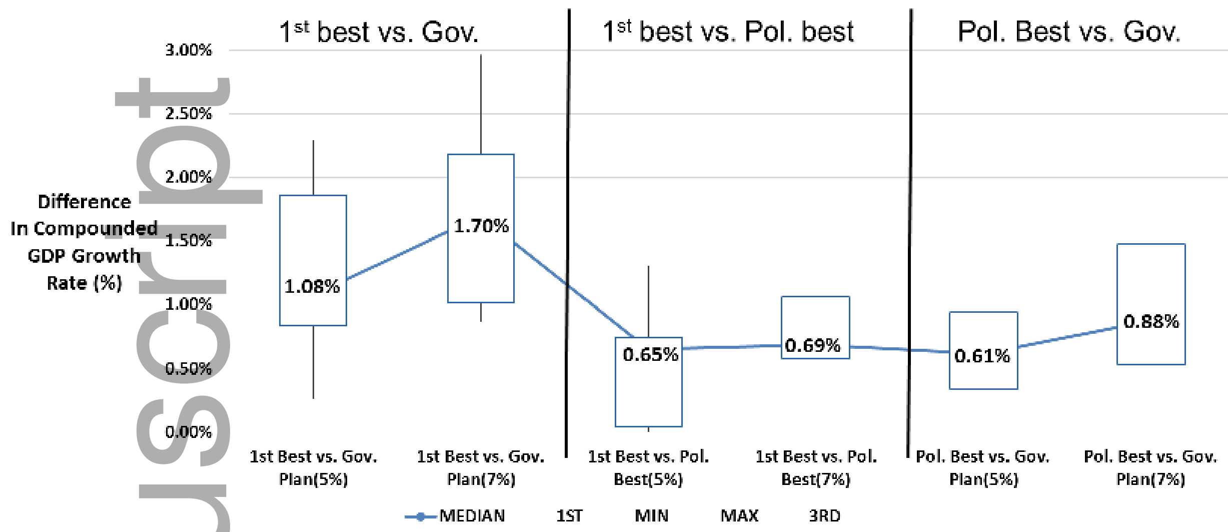

Figure 11: Boxplot of the difference in the compounded GDP growth rate among the first best, politically best and government's plan for various demand growth rates.

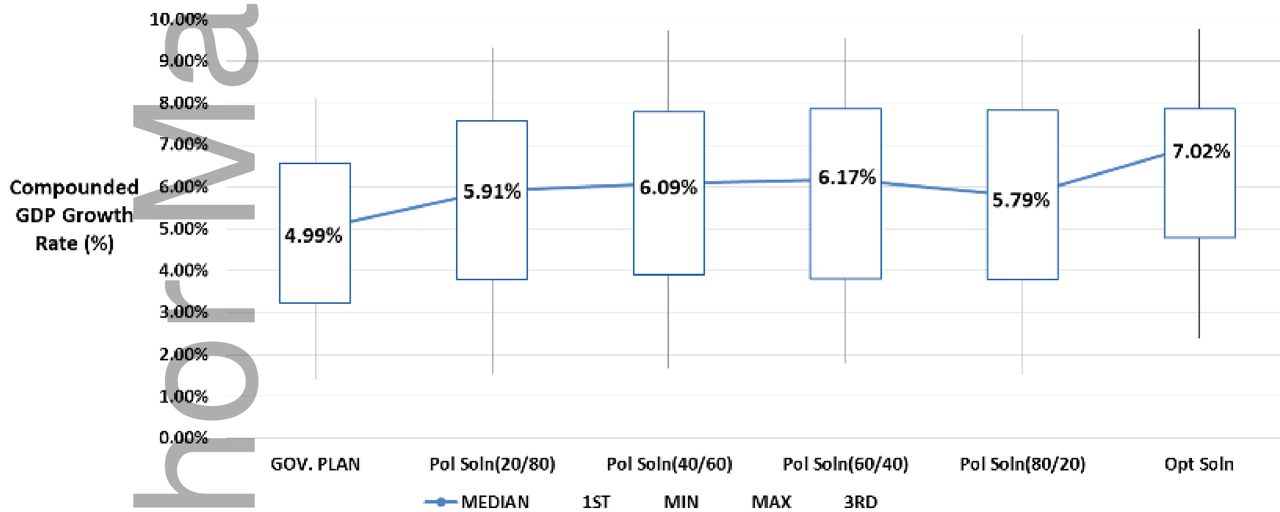

Figure 12: Boxplot of the compounded GDP growth rate for the first best, government's plan and politically best with various budget shares.

We next study the impact of budget share (between Punjab and Sindh) on the effectiveness of the politically best solutions in comparison to the first best and government's plan. As expected, Figure 12 shows that the first best performs the best and the government's plan performs the worst with the politically best solutions lying in between. Interestingly, the more balanced budget allocations (shares) among the provinces can achieve a better performance in the compounded GDP growth rate than the more extreme allocations.

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Lastly, we study the sensitivity of the solutions to random and exogenous additions to the energy mix. To this end, we introduce a random energy mix parameter, $\epsilon_t \in (0.5, 1]$, to represent the impact of exogenous and unpredictable additions (e.g., new hydro and other renewables). Specifically, only $\epsilon_t \times 100$ percent of the energy gap in each demand zone at time t needs to be met by the coal-fired energy supply chain. In this study, we consider 20 randomized instances with 3% budget, 15-year planning horizon, 5% demand growth rate, 60% share of budget by Punjab, and ϵ_t sampled uniformly in $(0.5, 1]$. Our randomized study (details omitted) shows that the first best and politically best solutions remain qualitatively the same as in the previous studies but with smaller improvements over the government's plan as the random energy mix parameter effectively reduces the energy gap, and so the observation is consistent to that made for a smaller demand growth rate (Figure 11).

Epilogue and Lesson Learnt

As illustrated in Section 1.2, the government's plan was the result of a political conflict between Punjab and Sindh provinces for resources. The plan seemed intuitive because first, it avoids the seemingly waste of exploring a limited reserve (Salt Range) that may soon run out, and second, the construction and operating costs of railway outweigh those of transmission. Although it was heavily debated, the plan became official because there is no scientific evidence to show its inefficiency and what the optimal plan should look like. Years passed before people finally realized that the plan was not practical and so dropped due to the heavy yield loss in transmission (Manan 2014, Pakistan Government National Power Policy 2013) and the government's poor budgetary conditions. Most recently, new plans similar to the politically best solutions were actually implemented as the country has started exploitation at both north (Salt Range) and south (Soda/Lakhra and Thar) in the same time (The News International 2014), and building coal-fired power plants close to demand zones (Manan 2014).

Combining the actual events with our results, we provide insights on why the government's plan failed and how to build up an energy supply chain for developing countries in general. The government plan fails for two reasons: (1) it ignores transmission yield loss and thus the cost trade-off of a coal-fired energy supply chain. Because power plants are very expensive to build, the cost of additional PPs (to make up the yield loss) outweighs the savings of railway. (2) The plan ignores the budget limits and the energy-economy cycle. Although Thar has the largest reserve, it costs too much up-front and takes too long to be effective. On the other hand, exploitation of the small reserve at Salt Range can quickly provide much needed energy to the starved economy; doing so can reverse the vicious energy-economy cycle by generating the economic growth and funding needed for future energy system development. Hence, the key insight (and lesson learnt) is that developing countries facing severe energy deficiencies need to consider both the cost and time trade-offs in building up energy supply chains. The cost trade-

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off, for a large part, determines the ultimate network configuration, while the time trade-off shapes up the best way to get there.

5 Conclusion

Energy deficiency and economic crises are correlated and commonplace in developing countries around the world. Fortunately, many of these countries are bestowed with abundant energy resources. A key to resolving the energy deficiency (and therefore economic crises) is the design of energy supply chains to utilize these sources effectively under limited budgets. The energy supply chains of developing countries have unique features that distinguish them from those of developed countries and material supply chains, such as, heavy yield loss of power transmission, the economy-dependent public budget, and the strong interaction between energy consumption and GDP. In this paper, we construct a novel mathematical model to capture these features and to optimize both the cost and time trade-offs found in these energy supply chains. Applying the model to the real life situation of Pakistan, we demonstrate its potential in breaking the vicious energy-economy cycle and in improving energy security and economic prosperity.

One condition for the model and solutions developed in this paper to be preferred is the objective of energy gap minimization, which makes sense to developing economies with a severe energy deficit. However, the impact of coal exploitation to the environment and local society cannot be ignored. In short term, measures should be taken to mitigate air pollution, fire hazards, ground deformation, and water pollution (Younger 2004). In long term, the government should achieve a more balanced energy mix through a combination of coal and other options such as oil, gas and renewable resources (hydro, solar and wind). The concept of energy supply chains and the modeling framework can be extended from coal to these energy resources where new models need to be developed to account for their distinct features and economics, and to optimally balance the energy mix from available sources. These developments may take the research to the next-level of complexity and we plan to conduct them in future studies. Finally, this paper may serve as a starting point of new model development at the interface between supply chain management and energy economics to aid decision makers in the developing countries to resolve the predicament of "*resource rich, energy poor*".

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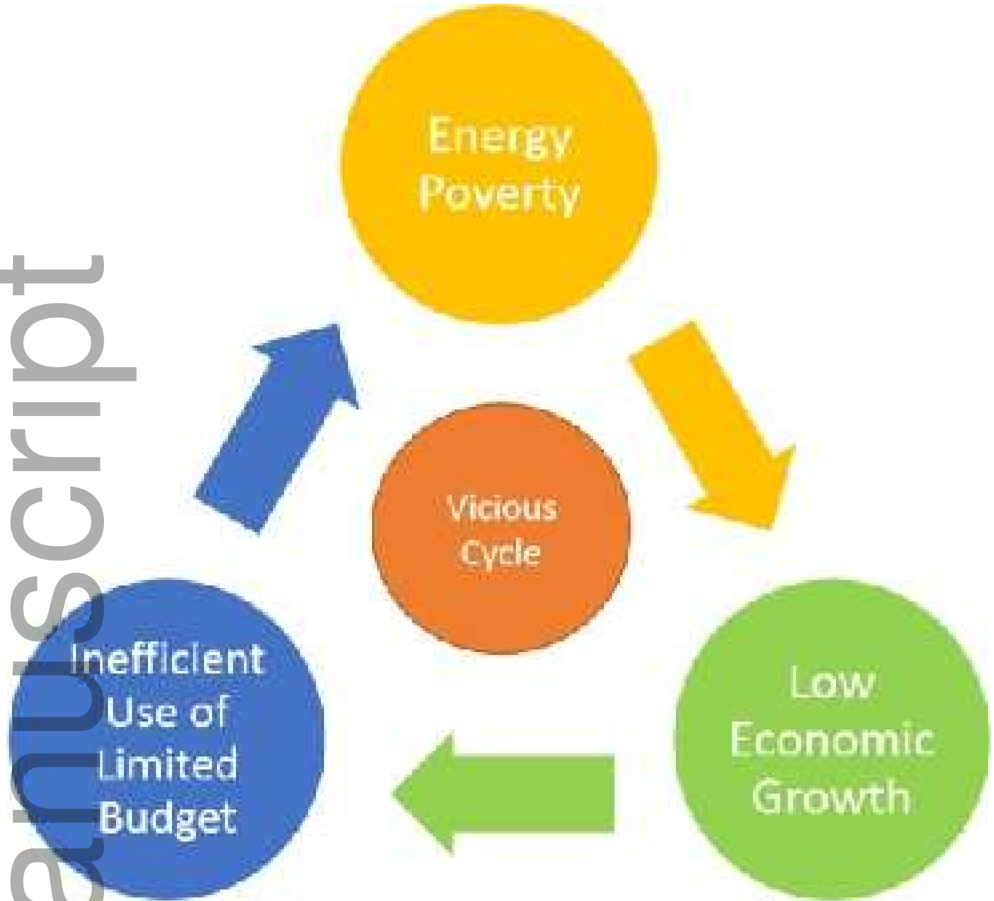

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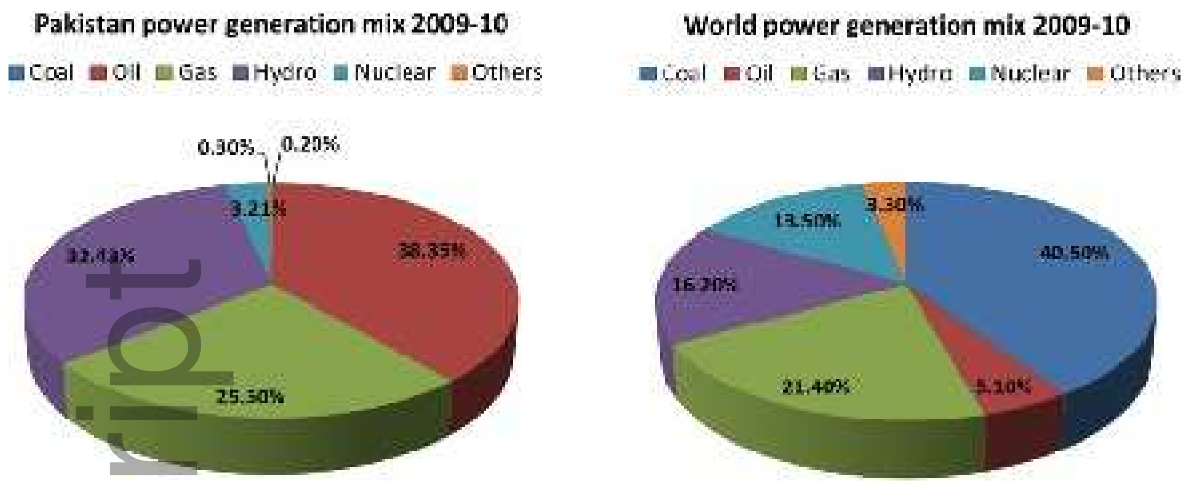

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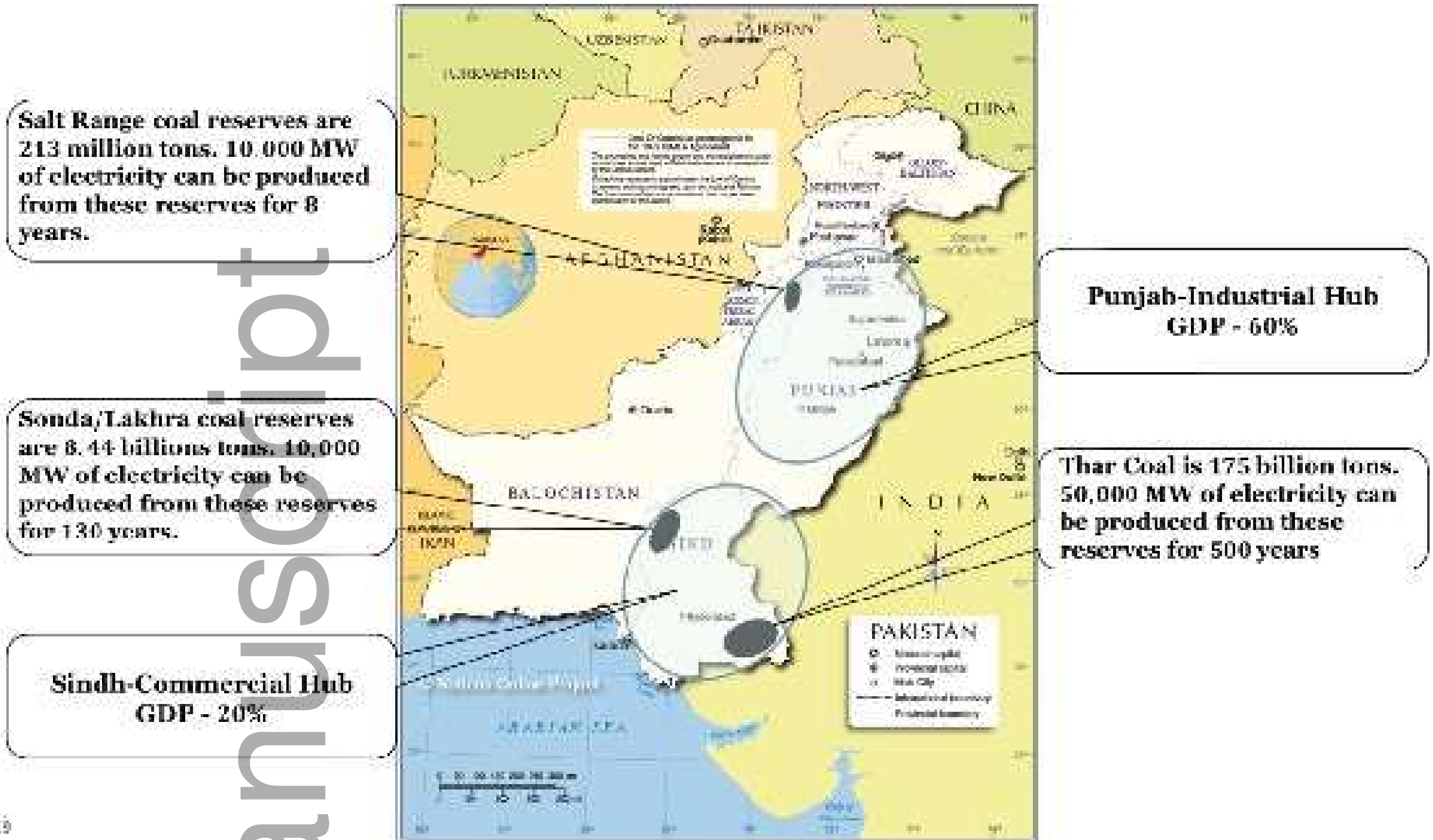

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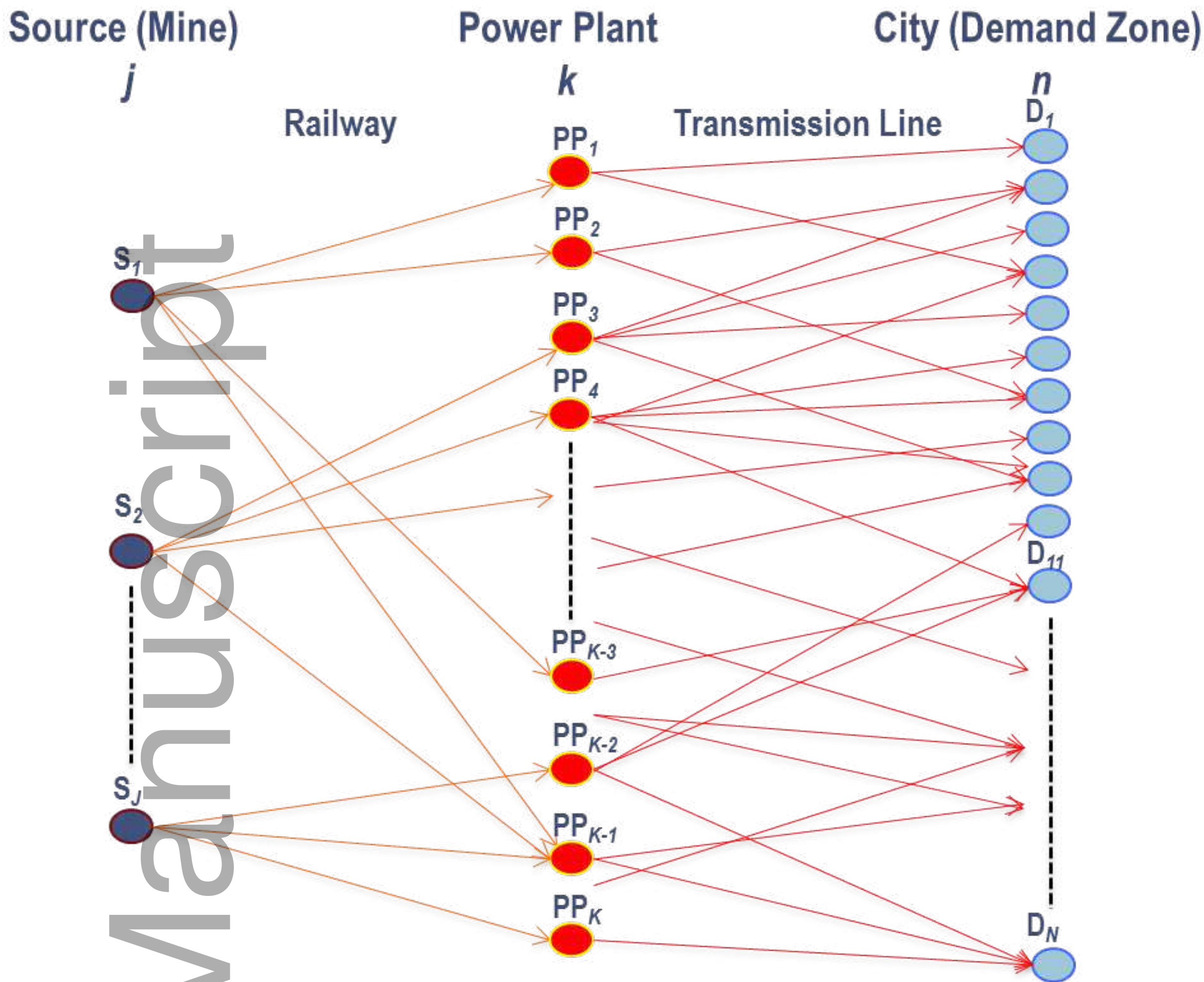

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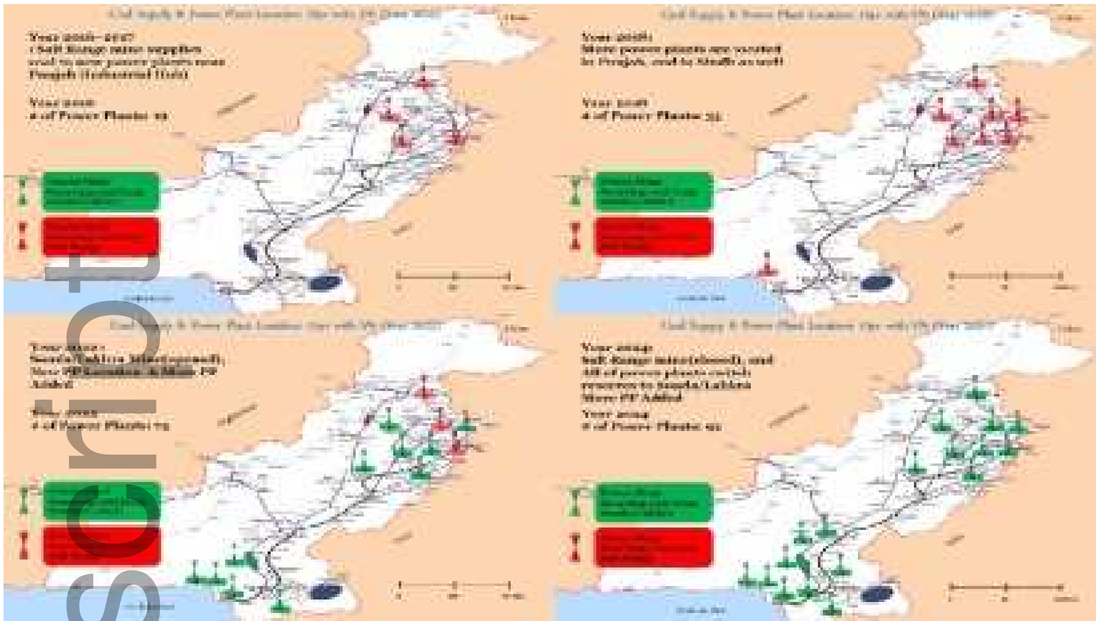

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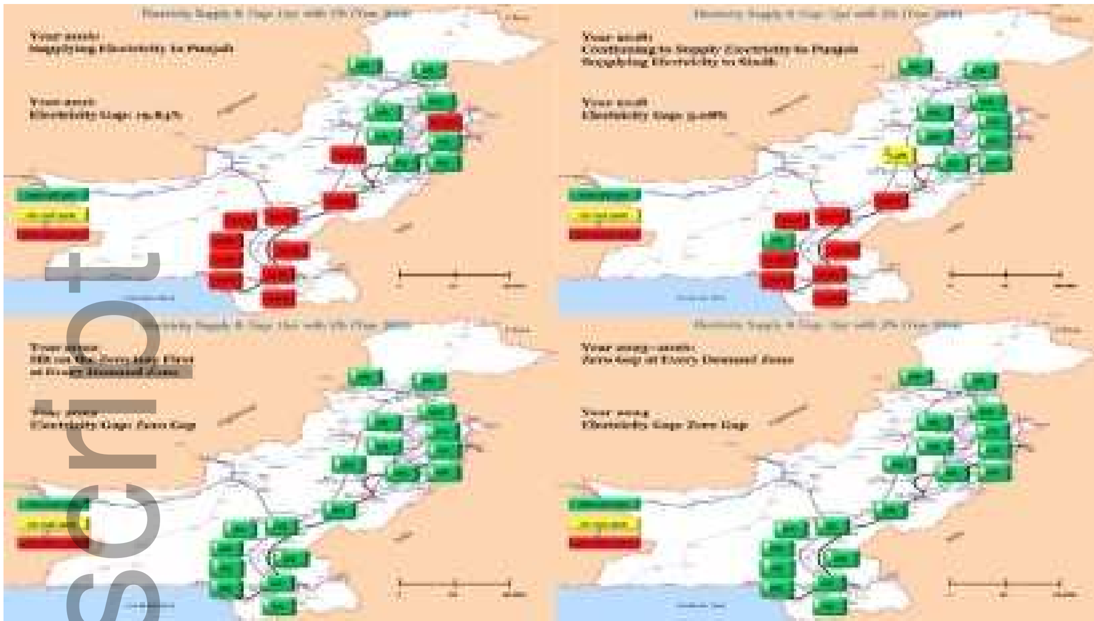

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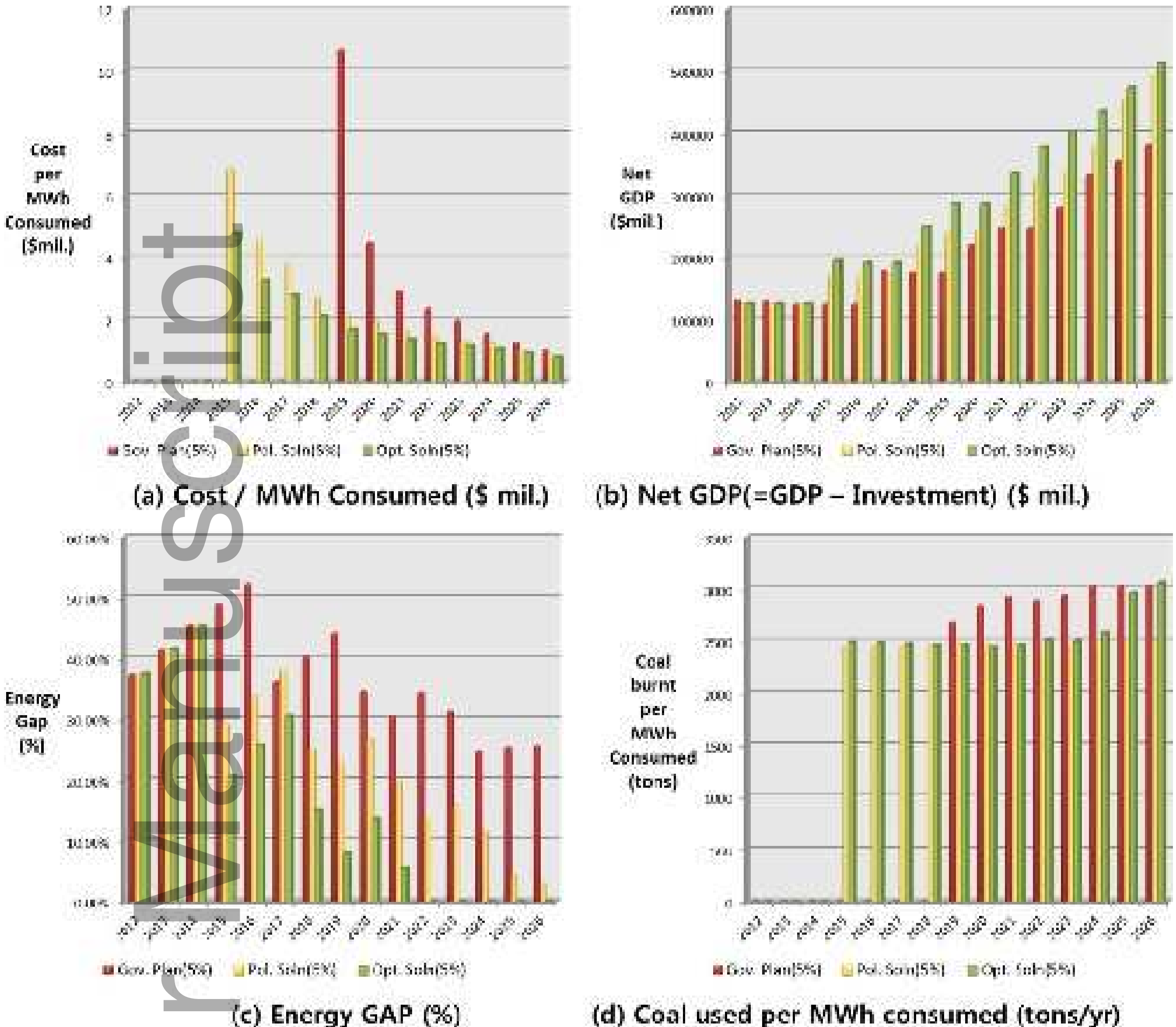

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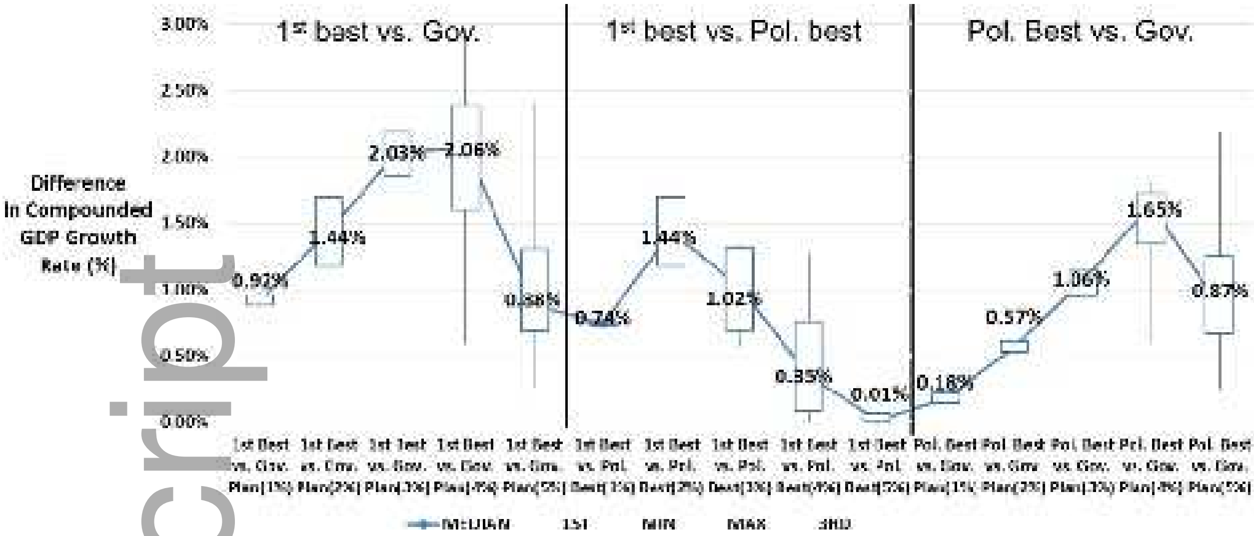

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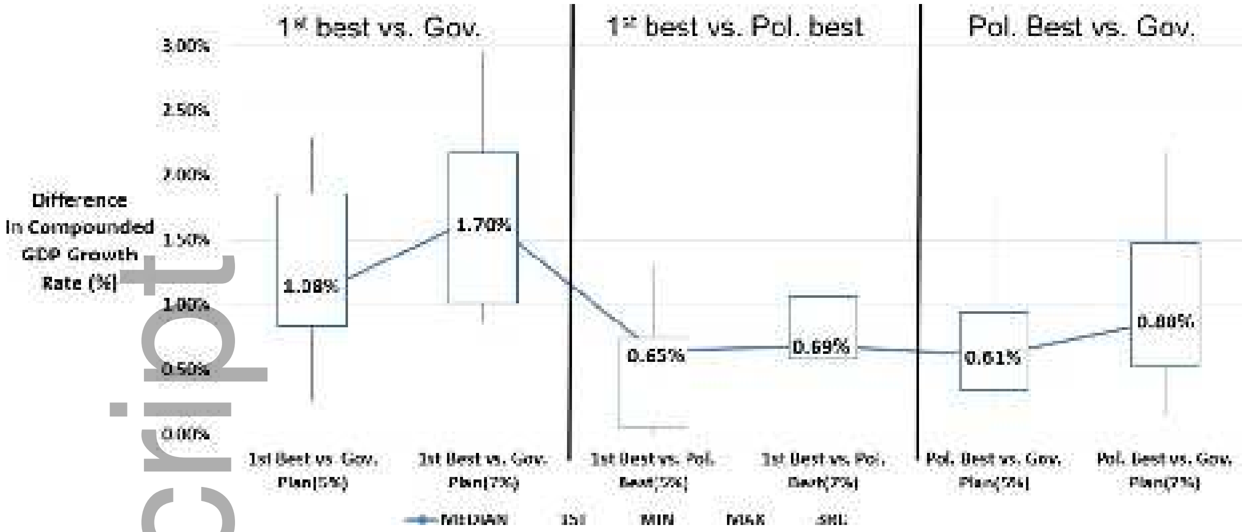

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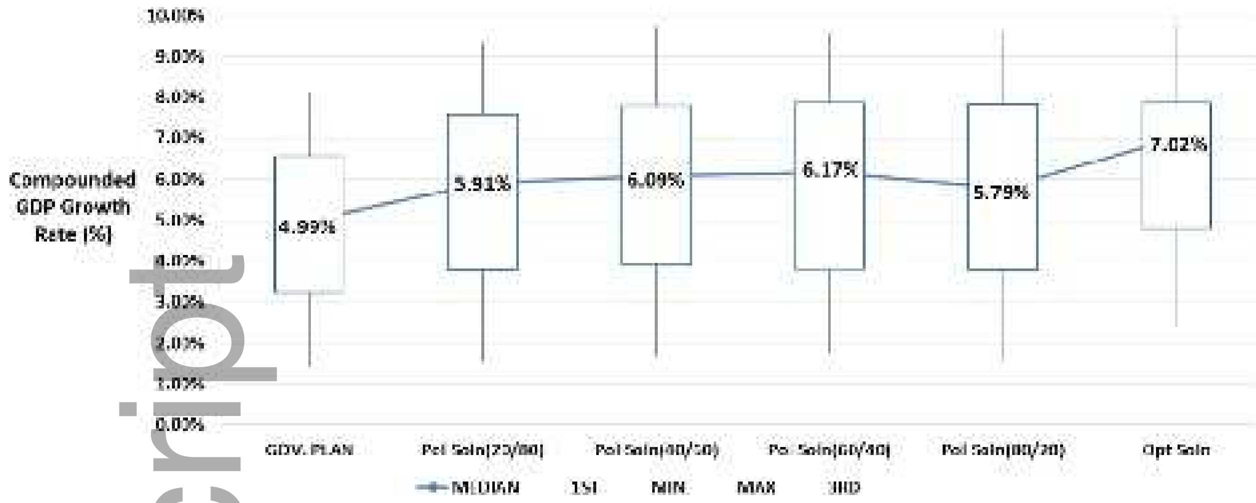

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