Optimizing Gas Management System Through
Underground Gas Storage Facilities:
A Case of Securing Energy Resources in Pakistan

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

Dedicated to my family, whose tremendous support and cooperation led me to this wonderful achievement.

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All due praise is given to Allah Almighty, the Creator and Sustainer, without whose guidance not a single minute pass. He has endowed us with strength and blessed us abundantly without measure. There are no words that can truly capture His greatness. I am enabled to read and write only by Him, who has granted me the knowledge I continue to share.

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ABSTRACT

Energy security is pivotal for Pakistan's stability. This study delves into 2012-2020 using the 4A framework—availability, accessibility, affordability, applicability—to scrutinize energy security. The rise of LNG underscores the complexity.

Amidst these energy challenges, natural gas assumes a crucial role. Underground storage emerges as a strategic tool to enhance energy resilience. This research evaluates its feasibility, delving into technicalities and in the end Optimization Model is built to optimize procurement of LNG and stored gas can be withdrawn at the time of higher demand or higher international prices.

In conclusion, this study navigates Pakistan's energy security amid global dynamics. The 4A framework guides this exploration, while underground storage offers resilience solutions for Gas System Optimization. Policymakers and stakeholders gain insights to bolster Pakistan's energy future.

Keywords: LNG: Liquified Natural Gas

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LIST OF ABBREVIATIONS

UGS	Underground Gas Storage
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
BCF	Billion Cubic Feet
GW	Gigawatt
MMSCFD	Million Standard Cubic Feet per Day
Tcf	Trillion Cubic Feet
PVT	Pressure-Volume-Temperature
SGS	Subsurface Gas Storage
API	American Petroleum Institute
EOR	Enhanced Oil Recovery
IOR	Improved Oil Recovery
EIA	Energy Information Administration
NG	Natural Gas
CNG	Compressed Natural Gas
E&P	Exploration and Production
MMBtu	Million British Thermal Units
ΔP	Pressure Drop
Q	Flow Rate
K	Permeability
h	Height
r1 and r2	Radial Distances
ΔP_wellbore	Wellbore Pressure Drop
F	Friction Factor
ρ	Fluid Density
L	Well Length
D	Well Diameter
A	Cross-Sectional Area

ΔP_total	Total Pressure Drop
P_wh	Wellhead Pressure
P_bh	Bottomhole Pressure
Q_inj	Injected Gas Volume
Q_prod	Produced Gas Volume
ΔV	Volume Change
Z	Compressibility Factor
R	Gas Constant
T	Temperature
V	Reservoir Volume

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Chapter 1. INTRODUCTION

Energy Security is important for the survival and prosperity of a country. It serves as foundation for economic and social standing of a country. Pakistan has always been a major importer of energy in the form of oil and since 2015. It has also started importing Gas in the form of Liquified Natural Gas (Malik et al., 2020). Due to fluctuation in the price of petroleum products in the international market, Pakistan's energy security remains volatile and exposed as serious threat to the export industry. Gas plays very important role now a days in Energy security of any country. Previously transportation of Gas was only possible through Gas Pipelines but now Gas is transported through liquification. Liquification reduced Gas Volume up to 600 times and have made it very transportable and affordable energy source around the world (IEA, 2021).

The goal of research is to evaluate energy security of Pakistan using 4A's framework over the last 9 years from 2012 to 2020. 4A's methodology comprises of 4 dimensions i.e. availability, accessibility, affordability and applicability (Malik et al., 2020). In this study scope of underground storage is evaluated and its impact in improving energy security of Pakistan.

Currently there is no underground Gas storage facility available in the Pakistan (Energy Year Book of Pakistan, 2019-20). All storage is in pipeline network. Due to the intake of LNG, there is an increase in the pressure of pipeline, production from our own fields' hiders. Gas from our own field is way too cheaper than imported LNG. By underground storage we can setup management system. We will be able to plan our procurements and make gas available at time of high demand (Daily or Seasonal) or at times of high international prices. Its technical aspects is discussed, and commercial viability is evaluated (Adedamola et al., 2021).

1.1 Background of the Research

The energy sector in Pakistan stands at a critical juncture, facing challenges related to energy security, sustainability, and economic growth. With a burgeoning population and increasing industrialization, the demand for energy resources has surged, revealing vulnerabilities in the energy supply chain. The country's heavy dependence on imported energy sources has exposed it to supply disruptions and price fluctuations in the global market. To address these pressing concerns, there is a need to explore innovative strategies that can optimize energy resources, enhance security, and pave the way for sustainable development.

Underground Gas Storage (UGS) emerges as a promising solution to bolster energy security. By storing excess gas during periods of low demand and releasing it during peak consumption times, these facilities offer supply flexibility and resilience against supply shocks (IEA 2020). However, effective utilization of such facilities requires sophisticated optimization techniques. The integration of advanced optimization algorithms, driven by Python programming and linear programming methodologies, holds the potential to streamline storage operations and contribute to energy security.

In this context, the **4A methodology**—focusing on Availability, Applicability, Acceptability, and Affordability—provides a comprehensive framework to assess energy security. This methodology allows for a holistic evaluation of factors shaping the energy landscape, encompassing resource availability, feasibility, stakeholder acceptance, and economic viability. By merging the insights from the 4A methodology with the optimization of underground gas storage, this research seeks to offer a multifaceted approach to enhance energy security in Pakistan. Through a meticulous examination of these dimensions, the study aspires to contribute insights that can inform effective energy policies, operational strategies, and sustainable growth in the energy sector.

As Pakistan navigates the complexities of its energy challenges, this research aims to bridge the gap between theoretical frameworks, technological applications, and policy formulation. By intertwining underground gas storage optimization with the 4A methodology, the study aims to offer a roadmap for a resilient energy future, one that not only ensures a secure energy supply but also aligns with the nation's economic, social, and environmental aspirations.

1.2 Research Rationale

Pakistan went through terrible energy crisis, and we countered that crisis with high-price energy deals that run on expensive imported fuel. Pakistan’s energy security is exposed to the price fluctuations in the international market (Malik et al., 2020). We don’t have any storage facility that’s why we can’t import at lower price and utilize it during high demand and high price time. Sometimes, delay in procurement of LNG Cargos has led to the scarcity of gas in the country which subsequently resulted in the shut-down of Power Plants, Industries and fertilizer manufacturing. Energy security is also linked with food security and social security of country which contributes in overall National Security of a country (World Bank, 2020).

Pakistan is strategically located between World’s Largest Gas Reserves of the world (Middle East and Central Asia) and World’s big energy importers (China and India). Pakistan signed two agreements for Gas Import through Pipeline. One was with Iran and the other one was with Turkmenistan (TAPI) (Kanwal et al., 2022).

Economics play a vital role in viability of any project. Currently, we have 20% line-losses and because of this, our marketing companies are in losses or unaccounted for gas volumes (Pakistan Energy Year Book 2019-20). Pakistan needs to improve its distribution system in order to tap into this huge opportunity. This is also impossible without establishing underground storage facilities in the country.

1.3 Research Problem

The energy landscape of Pakistan faces multifaceted challenges and complexities that necessitate a comprehensive investigation to ensure sustainable energy security. With a growing population, increasing energy demand, and a heavy reliance on imported energy sources, Pakistan's energy security becomes a paramount concern. Underground Gas Storage facilities can provide an opportunity to optimize gas management of Pakistan. In this context, this research aims to address the following key research problem How can the optimization of underground gas storage facilities be integrated with the 4A methodology to enhance energy security in Pakistan and contribute to a sustainable energy policy?

This research problem necessitates an exploration of the intricate interplay between underground gas storage, optimization techniques, the 4A methodology, and energy security considerations in Pakistan. By addressing this problem, the study seeks to provide valuable insights that contribute to the formulation of effective energy policies, strategies, and operational practices that can enhance Pakistan's energy security in the face of dynamic challenges and uncertainties in the energy market.

1.4 Problem Statement

Scarcity of Natural Gas can put Pakistan's economic and social security at high risk. Germany alone has capacity to store 80 days of its need from imported Natural Gas in underground storage facilities. In Pakistan, we have second largest CNG converted cars in the world after Iran but unfortunately due to the unavailability of gas, CNG Stations are shut down. LNG/Gas is still cheaper in comparison to oil (IEA, 2021). If we are able to manage Gas, then we can save large amount of money that we pay for Crude oil Import.

Pakistan is facing a severe energy security challenge. The country's rapidly growing energy demand is outpacing its limited indigenous energy resources, leading to a high reliance on imported energy which is expensive and unreliable. The country's poorly developed energy infrastructure further compounds the problem. Due to the absence of UGS, Pakistan is exposed to the fluctuations in the global Fuel prices and there no option to optimize the system.

1.5 Definition of Terms

Following important terms need to be introduced for better understanding of remainder of the report,

Underground Gas Storage Modelling: The process of creating mathematical or computational representations of subsurface geological formations used to simulate the behaviour of gas storage, withdrawal, and reservoir dynamics.

Reservoir Simulation: The numerical approximation of reservoir behaviour, considering factors such as fluid flow, pressure, temperature, and composition to predict gas storage performance.

Porosity: A measure of the void space within a geological formation, essential for determining the volume of gas that a reservoir can hold.

Permeability: The ability of a reservoir rock to allow the movement of fluids, influencing the flow rates and efficiency of gas injection and withdrawal.

Injectivity and Deliverability: Injectivity refers to the rate at which gas can be injected into a storage reservoir, while deliverability indicates the rate at which gas can be withdrawn.

Formation Volume Factor (FVF): The ratio of the volume of gas at reservoir conditions to its volume at surface conditions, crucial for converting between reservoir and surface measurements.

Material Balance Equation: A fundamental equation used in reservoir modelling to track changes in gas volume, pressure, and composition over time, aiding in performance analysis.

History Matching: The process of adjusting model parameters to match historical data from the reservoir's behaviour, ensuring accurate representation and prediction.

Wellbore Storage and Skin Effect: Wellbore storage refers to the compression of gas in the wellbore during injection, while skin effect represents the alteration of reservoir properties near the wellbore due to drilling and completion.

Gas Cycling: The practice of injecting gas during periods of low demand and withdrawing it during peak demand, optimizing reservoir utilization and maintaining supply stability.

4A Methodology: A comprehensive approach to assessing energy security that focuses on four dimensions Availability, Accessibility, Affordability, and Acceptability.

Availability of Energy Resources: The presence of reliable and diverse energy sources to meet current and future energy demands, ensuring a stable supply.

Accessibility of Energy Resources: The ease of physically obtaining energy resources and the development of infrastructure to transport and distribute them efficiently.

Affordability of Energy Resources: The consideration of energy costs in relation to individual and national income levels, ensuring that energy remains economically accessible.

Acceptability of Energy Resources: The evaluation of environmental, social, and cultural factors associated with energy sources, promoting sustainable and socially acceptable options.

Energy Mix Diversification: The strategy of utilizing a variety of energy sources to reduce dependency on a single source and mitigate supply disruptions.

Objective Function: The goal of a Linear Programming problem is to either maximize or minimize an objective function. This function represents the quantity that needs to be optimized. In this case, it's the total cost of gas procurement.

Decision Variables: These are the variables that need to be determined in order to achieve the objective. In your case, the decision variables are the amounts of gas procured for each month.

Constraints: Constraints are the limitations or restrictions on the decision variables. They represent the practical limitations of the problem. For example, the constraint that the total procured gas should be 40 BCF.

Linear Relationships: Linear Programming assumes that the relationships between the objective function and the constraints are linear. This means that the objective function and constraints can be represented by linear equations or inequalities.

Optimization: The goal of Linear Programming is to find the values of the decision variables that satisfy all constraints while optimizing the objective function. The optimal solution is the set of decision variable values that either maximize or minimize the objective function, depending on the problem type.\

1.6 Thesis Structure

The thesis follows a structured framework designed to comprehensively explore the topic of "Optimizing Gas Management System through Underground Gas Storage Facilities A Case of Securing Energy Resources in Pakistan." The structure encompasses distinct chapters, each serving a specific purpose in advancing the research. Chapter 1 introduces the background, problem statement, objectives, and significance of the study. Next delves into a comprehensive literature review covering energy security, underground gas storage, the 4A methodology, and related concepts. Chapter 3 details the research methodology, including data collection, reservoir modelling, and the application of optimization algorithms. Chapter 4 interprets the results, discusses their implications, and compares findings with existing literature. Finally, Chapter 5 offers a conclusion summarizing the research, its contributions, future research possibilities, and the broader significance of the study.

Chapter 2. LITERATURE REVIEW

2.1 Energy Security

Energy security is a concept that encompasses a variety of disciplines, but at its core, it is about ensuring a reliable energy supply during times of both abundance and scarcity. Research can explore disruptions or reduced energy security in an economy to understand the impact on the overall economic well-being (Malik et al., 2020)

Meeting four key conditions is essential to ensure energy security for end-users, as outlined by the 4As framework. These include the availability of sustainable energy resources that are either indigenous or renewable, the economic applicability of technologies and infrastructure to extract and harness energy resources, the acceptability of the environmental and social impacts of energy sources, and the affordability of energy sources for end-users. This framework was proposed by Yao and Chang in 2014.

The energy security challenge of today goes beyond oil supplies and includes various issues related to energy policy, such as promoting access to modern energy and addressing climate change (Cherp and Jewell, 2014). As a result, the concept of energy security has evolved to address these broader concerns and has incorporated new dimensions, including the environment, human security, international relations, foreign policy, energy efficiency, and capacity adequacy (Yao and Chang, 2014). Due to the many frameworks and dimensions discussed in regional and country-specific studies on energy security, contemporary energy security can be viewed as "multidimensional" (Yao and Chang 2014). Additionally, it is important to take into account the impact of "disruptive innovations" on the future energy landscape during discussions on energy security (Proskuryakova, 2018).

Martchamodol and Kumar (2012) explain that energy security in developing nations involves meeting primary energy demand at stable prices for improved economic performance, poverty alleviation, and environmental sustainability. In contrast, developed countries focus on cost-effective energy production and accessibility for all. Victor and Yueh (2010), Vivoda (2010), Yergin (2006), Yao and Chang (2014), and Malik et al. (2020) emphasize the complexity of understanding and evaluating energy security due to its multi-dimensional nature and regional differences.

2.1 Modelling Framework

Multiple studies have utilized various energy modelling frameworks and techniques to evaluate the energy and power planning policies in Pakistan. (Mirjat et al. 2017) surveyed all the available power planning studies and energy and power planning policies implemented by the Government of Pakistan since 1947, suggesting the use of the long-range energy alternative planning (LEAP) tool for integrated energy planning and policy formulation. However, it did not provide any conclusions regarding the state of energy security in Pakistan. (Aized et al., 2018) utilized the LEAP model to present four scenarios that analyse the renewable energy policy of Pakistan and suggest suitable options for securing energy supplies in the future. Additionally, a study examined the relationship between energy security and economic growth by using the error correction model (ECM) (Mahmood and Ayaz, 2018). The energy gap, a crucial metric for energy security, was found to have a significant negative impact on economic growth, and reducing reliance on imported fuel and improving the energy mix can decrease this energy gap, leading to socio-economic and environmental sustainability. (Khawaja and Rehman, 2016) emphasized the expansion of electricity and gas trade with Central Asia to meet energy diversification and security goals.

Various energy modelling frameworks and techniques have been used to analyse energy and power planning policies in Pakistan, with studies demonstrating a continued heavy reliance on fossil fuels in the overall energy mix in the future. There is a need for the adoption of renewables and the removal of barriers to their use, such as aging infrastructure and policy gaps. The sustained supply of hydrocarbon resources in the future is also necessary. Scenarios of renewable portfolio supply (RPS) in the energy mix and carbon tax have shown positive impacts, such as reduced dependence on imported fuel, decreased energy intensity, and greenhouse gas (GHG) mitigation. However, there has been no comprehensive analysis to quantify the energy security in Pakistan, which this study aims to address. Using the 4As framework and a set of indicators, this study quantifies Pakistan's energy security for the period 2012-2020, tracks trends, and prioritizes areas in the energy value chain to achieve greater energy security. The method and results of this study could be useful for other countries with similar energy demand patterns.

2.2 Energy Security and 4A’s Framework:

Some studies have overcomplicated energy security analysis by incorporating numerous indicators. (Sovacool and Mukharjee, 2011) suggest that the choice of indicators should depend on data availability and not exceed 20. (Yao and Chang, 2014) proposed the 4As framework, which simplifies energy security analysis into four dimensions: Availability, Applicability, Acceptability, and Affordability.

Yao and Chang (2014) used the 4As framework to assess China's energy security over the past three decades, revealing fluctuations in energy security levels. Tongsopit et al. (2016) applied this framework to measure energy security in ASEAN countries, finding that several indicators deteriorated, emphasizing the need for indicator-based frameworks and renewable energy development. Li and Chang (2019) demonstrated that Electric Vehicle (EV) penetration, combined with aggressive fuel economy policies, could enhance energy security by relying on indigenous renewable energy sources and reducing fossil fuel dependence.

Malik et al. (2020) conducted an analysis of Pakistan's energy security status using the 4As framework from 2011 to 2017, revealing significant improvements in the initial years followed by a decline due to heavy reliance on imported fossil fuels. To address this issue, they recommended increasing the utilization of domestic renewable energy sources and green energy initiatives, such as grid connectivity, demand-side measures, and small hydroelectric projects.

Obadi and Korcek (2020) assessed the energy security levels of several European Union (EU) countries from 2006 to 2017, employing the Z-score standardization method. Italy scored the highest due to improved energy supply diversity, while France's score decreased due to resource availability issues. Poland and Slovakia also experienced reduced energy security levels due to environmental concerns and technological limitations.

Recognizing the global significance of energy security, Azzuni and Breyer (2020) introduced a novel approach to create an energy security index based on 15 dimensions. They emphasized the need to avoid one-size-fits-all strategies for improving global energy security due to country-specific variations and highlighted the importance of learning by doing for sustainability-driven energy security enhancements.

Azzuni et al. (2020) investigated the impacts of a 100% renewable energy transition for Jordan by 2050, using a qualitative approach with color codes. The study revealed that this transition would positively affect five out of six chosen energy security dimensions, with diversity remaining neutral. Cost, employment, health, environment, and availability dimensions would significantly improve, emphasizing the need for further empirical investigations to optimize energy transition strategies for Jordan.

Abdullah et al. (2020) adopted an integrated approach to analyze Pakistan's energy security level from 1991 to 2018, incorporating five dimensions, including two from the 4As framework (Availability and Affordability) and three additional dimensions (Technology, Governance, and Environment). The study observed a decrease in Pakistan's energy security level from 1991 to 1999, followed by consistent improvements. These positive outcomes were attributed to improved energy resource supply, consumption levels, and stable import indicators.

2.2.1 Availability

In the framework, the availability dimension signifies the presence and adequacy of fossil fuels and other locally sourced energy resources to fulfil the energy needs of a region. A region's ranking on this dimension is positively correlated with the extent of reserves, potential, and adequacy of indigenous energy resources (Malik et al., 2020). This research evaluates Pakistan's performance regarding the availability dimension using the following set of four indicators:

- Share of Imported Oil Supply
- Share of Imported Gas Supply
- Share of Imported Coal Supply
- Hydroelectric Power Generation

A higher reliance on energy imports results in a lower ranking on the availability dimension, while increased generation of power from domestic resources such as hydropower leads to a higher ranking on the availability dimension.

2.2.2 Applicability

The applicability dimension assesses a region's capability to harness and expand its reserves of native energy sources. It encompasses the utilization of innovative technologies to reduce energy wastage, enhance energy conservation, and consequently, extend the utilization of existing energy reserves, contributing positively to the applicability score (Yao and Chang, 2014). Additionally, adopting advanced technologies that augment the size of a nation's indigenous energy reserves by extracting previously inaccessible resources elevates its ranking on the applicability scale. This study evaluates Pakistan's performance regarding the applicability dimension employing a set of four key indicators:

- Efficiency of Power Generation from Gas
- Count of Newly Drilled Exploratory Wells for Oil and Gas
- Energy Intensity in the Agricultural and Transportation Sectors
- Energy Intensity within the Industrial Sector

Notably, a substantial portion of Pakistan's electricity generation relies on natural gas. Enhancing the efficiency of gas-based power plants or conversely, reducing energy losses during electricity generation can curb the depletion rate of the country's gas reserves, thereby strengthening its energy security (Malik et al., 2020)

During the past decade (2000–2010), Pakistan experienced a slowdown in oil and gas drilling activities, attributed to a lack of policy support, government commitment, and security challenges stemming from neighboring Afghanistan's War on Terrorism (Malik et al., 2020). However, following a change in government in 2013 and various military operations aimed at enhancing security in high-potential areas, Pakistan has witnessed a resurgence in oil and gas drilling activities. Elevated drilling activities heighten the likelihood of discovering substantial reserves, which, in turn, can bolster the nation's energy security. Moreover, calculating the energy intensity of a sector involves dividing the total energy consumed in a year by the sector's generated GDP (measured in million Pakistani rupees). It signifies the amount of energy utilized for each rupee earned within the sector. A reduction in energy intensity indicates improved efficiency, enhanced energy conservation, and consequently, an uplift in energy security. This reduction may also stem from structural changes within the sector. For instance, if certain energy-intensive industries reach saturation in terms of demand and new investments shift towards sectors with better returns or unmet demand, the industrial sector's energy intensity can decrease. In such a scenario, the country can be considered as enhancing its energy security by maintaining or expanding its industrial GDP with reduced energy consumption. (Malik et al., 2020)

2.2.3 Acceptability

The acceptability dimension encompasses the evaluation of social and environmental factors associated with the integration of new energy sources. For the successful adoption of such sources, it is imperative to transparently address any social and environmental barriers (Tongsopit et al., 2016). Shifting a region's energy mix to augment the proportion of renewable energy contributes positively to its energy security. However, it's crucial to acknowledge that various renewable sources, including nuclear, hydropower, solar, and wind, each encounter distinct challenges in the realms of societal acceptance and environmental impact (Amin et al., 2022)

For instance, the Fukushima nuclear plant disaster in Japan following the 2011 earthquake and tsunami cast doubts on the future of nuclear power generation, highlighting the significant social and environmental concerns associated with this energy source. Moreover, the declining costs of wind and solar energy have rendered nuclear power less economically competitive. Consequently, nuclear power generation, except in the People's Republic of China, experienced a three-year consecutive decline from 2015 to 2017, despite the global growth in wind and solar power output (Schneider et al., 2018). The emergence of safer and more cost-effective alternatives has led to increasing opposition against new nuclear power projects due to safety apprehensions. (Malik et al., 2020)

This study evaluates Pakistan's performance regarding the acceptability dimension utilizing four key indicators:

- Proportion of Nuclear and Renewable Energy in Power Generation
- Per Capita CO2 Emissions
- Pakistan's Contribution to Global CO2 Emissions
- Diversity of Energy Sources and Adoption of Novel Sources

2.2.4 Affordability

The affordability dimension encapsulates an economy or society's capacity to acquire energy resources at a cost that is reasonable and accessible across all income groups (Tongsopit et al., 2016). It underscores the importance of ensuring that energy remains accessible to people from various socioeconomic backgrounds. A decline in affordability within a country signifies reduced accessibility, implying an incapability to adequately fulfill the energy requirements of its population.

In this study, Pakistan's performance concerning the affordability dimension is assessed using the same four indicators

- Energy Supply per Capita
- Gas Price
- Electricity Price
- Gasoline Price

2.3 Energy Security of Pakistan

During a literature review of Pakistan's energy security, researchers discovered that most studies have evaluated the energy situation in a qualitative manner concerning areas such as energy supply and demand, policy review, primary energy mix, and generation capacity planning (Aized et al., 2018; Mirjat et al., 2017; Nawaz and Alvi, 2018). (Anwar, 2014) have extended beyond qualitative discussions and provided quantitative analyses of the "impact" of various factors such as the government's policy decisions, dependence on primary energy imports, and economic factors on energy security. Nonetheless, none of these studies have established a reference quantitative measure of Pakistan's energy security (Malik et al., 2020).

A study conducted by (Anwar, 2016) analysed the impact of reducing energy imports by 5%, 10%, and 15% on Pakistan's energy system using MARKAL for the period of 2005-2050. The results showed a slight decrease in primary energy supply and import fuel dependency, with a relatively greater addition of renewable energy to the mix. This diversification of resources can reduce the vulnerability to energy imports and enhance energy security. However, the study did not consider the individual impacts of LNG and coal imports, which are expected to make up a significant part of Pakistan's energy mix in the future. Moreover, the study did not account for the effects of enhancing the energy system's efficiency or the affordability for end-users (Amin et al., 2022).

2.4 Pakistan’s Energy Sector

Pakistan's energy history has been shaped by the discovery of large natural gas reserves since the 1950s. These discoveries led to the growth of the domestic fertilizer industry and large public-sector gas distribution utilities in the 1960s. From the mid-1970s to the 1990s, all major power plants established by the government were based on dual fuel, with natural gas as the primary fuel (Kanwal et al., 2022). By 2005, natural gas accounted for approximately 50% of Pakistan's primary energy mix. However, with no significant gas field additions since then, gas production has stagnated, and the country has become increasingly reliant on imported oil to meet its energy demand. To offset the decreasing share of local gas supplies, Pakistan has been importing higher amounts of coal and LNG. As of 2017–18, indigenous gas supply made up approximately 35% of the country's total primary energy supplies, while oil accounted for 31% (Ministry of Energy, 2018).

2.5 Pakistan Energy Mix

During the early 2010s, Pakistan underwent extensive electricity and gas supply deficits. Rural areas and other parts of the country experienced blackouts for 8-12 hours per day during peak summer months, and low gas pressure or inadequate supplies during peak winter months. However, in 2013, a new government was elected with the aim of eradicating the energy deficits. Over the next 5 years, Pakistan made significant investments in its energy infrastructure, adding a minimum of 10 GW in new power generation capacities (including roughly 2 GW from coal) and initiating 1.3 billion cubic feet per day of LNG-importing infrastructure. As a result, Pakistan succeeded in decreasing its energy shortages, but it now faces structural challenges such as enhancing energy security by decreasing the proportion of imported fuels and reducing the cost of energy (Yousaf Raza & Lin, 2023).

In the fiscal year 2017-18, almost 37% of Pakistan's primary energy supplies were consumed for power generation. However, during generation, over 55% of the primary energy used for electricity was lost, and an additional 7% was lost during transmission and distribution. The losses tend to be high in thermal power plants, ranging from 40% to 60%. Although some of these losses are due to Pakistan's degraded power generation assets, such losses are typical worldwide due to technological and operational limitations. After such significant losses, households and the residential sector purchase around 50% of the final electricity sold on the grid (Pakistan Energy Yearbook 2017-18). This means that overall, Pakistan uses approximately 18% of its primary energy supplies to provide electricity to households (including the associated losses incurred in generating and supplying this electricity). Pakistan cannot sustainably provide thermal fuel-based electricity to homes, which is not an income-generating activity. To reduce energy imports, Pakistan must introduce and promote green energy solutions like rooftop solar solutions for homes and commercial buildings and better building insulation. In addition, households consume another 7%-8% of primary energy supplies in the form of gas for cooking and heating. To shift this demand to renewables, there is a need to adopt home appliances like solar-powered water heaters and electric stoves to replace gas-based heaters and stoves (Malik et al., 2020).

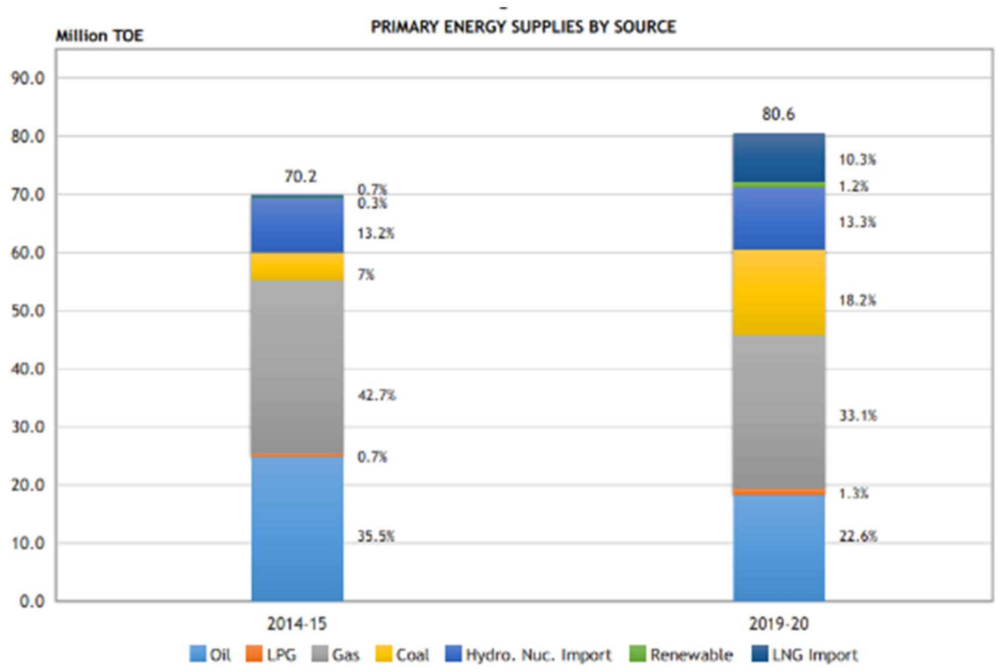

Figure-1-1 Primary Energy Supplies of Pakistan (Energy Year Book 2019-20)

2.5.1 Natural Gas

In 2005, natural gas accounted for around 50% of Pakistan's primary energy mix, but with no significant increase in gas field discoveries, the production of gas has stagnated. Presently, natural gas only makes up about 35% of the country's primary energy mix (Pakistan Energy Yearbook 2017-18). Pakistan heavily relies on imports for its energy supplies, with oil, coal, and LNG constituting almost one-third of its total energy mix. However, as local gas reserves continue to deplete, the country is projected to increase its dependence on energy imports. The Oil & Gas Regulatory Authority predicts that local gas production will drop from approximately 4 billion cubic feet per day to 2 billion cubic feet per day by 2025, while the demand for gas is expected to increase by 1.5 billion cubic feet per day. If the energy imports were to replace this additional 3.5 billion cubic feet per day of gas shortage, Pakistan's energy imports would more than double (measured in tonnes of oil equivalent) (Yousaf Raza & Lin, 2023).

2.5.2 Oil

More than 85% of the oil and petroleum products consumed in Pakistan are imported. There has been a significant shift in the components of oil consumption since 2014. The power sector's share in oil consumption has decreased considerably, while the transport sector's share has increased due to the newer installed power plants moving towards cheaper fuels. On the other hand, the increase in the share of transport is mainly due to the decline in domestic petrol prices and higher imports of used cars. During July-February in the FY 2017-18, the share of transport in oil consumption increased to 64.4% compared to 57.2% during the same period in the previous year (Pakistan Energy Yearbook, 2017-18). However, the share of power decreased to 26.4% from 33.2% due to the availability of cheaper alternative power sources such as LNG, hydro, and coal.

2.5.3 Coal

Pakistan possesses substantial coal reserves of over 186 billion tons, which can meet the country's energy demands on a sustainable basis. The production of coal from the Thar coalfield is expected to increase in the coming years. Presently, indigenous coal production is mostly used by brick kilns, with a small quantity used by cement factories. Imported coal is used by power plants, cement manufacturing units, Pakistan Steel, and other industries (Abdullah et al., 2020). Due to the construction of new coal-based power plants at Sahiwal and Port Qasim, the imports of coal have increased significantly in comparison to the previous fiscal year (FY 2016-17).

2.5.4 Hydro Power

It is estimated that Pakistan has the potential to generate 40 GW of hydropower, however, the installed capacity of hydro-based power currently stands at only 8 GW (excluding micro-hydel power projects with a size ranging from 5 kW to 100 kW). The government is the primary owner of the operating hydro-power projects. Private investment in hydro projects has been limited due to extended project gestation periods, tariff-related challenges, and competition from solar and wind projects (Yousaf & Lin, 2023). Pakistan has also effectively implemented micro-hydro power projects to provide electricity to off-grid communities. These projects are typically community-led initiatives in partnership with local governments or non-profit organizations, and sometimes receive funding from international donor agencies (Malik et al., 2020).

2.5.5 Renewable – Solar and Wind

In the last half-decade, eighteen wind power projects with a combined capacity of 937.27 MW have become operational and are providing electricity to the national grid. Additionally, six solar power projects with a capacity of 418 MW have been commissioned. Due to their small investment size and short gestation period, wind power projects have garnered the highest level of private sector interest, while utility-scale solar power projects, which require large amounts of land, have not been as attractive to private investors. The rooftop solar solutions industry (Abdullah et al., 2020).

2.6 Energy Security and Underground Gas Storage (UGS)

"UGS storage is a key enabler of energy security, providing a reliable and flexible source of gas that can be used to meet peak demand and mitigate supply disruptions," as noted by the (International Energy Agency, 2021). This strategic reservoir serves as a safeguard against supply fluctuations and supply chain disruptions, ensuring a consistent gas supply during peak demand periods. Its significance lies in its ability to fortify a nation's energy infrastructure.

"UGS is a cost-effective way to store natural gas, making it an attractive option for countries that are looking to improve their energy security," as highlighted by the (World Bank, 2021). The cost-effectiveness of UGS renders it a compelling choice for countries keen on fortifying their energy security. UGS emerges as a pragmatic solution to store natural gas efficiently, a factor that is especially attractive to nations aiming to enhance their energy resilience while optimizing expenditure on energy resources.

One of the distinctive advantages of UGS is its potential to curtail the volatility of energy prices, thus contributing to enhanced affordability for consumers. This impact on price stability can mitigate the financial burdens faced by households and industries. The European Association for the Storage of Natural Gas (2022) underscores how UGS can play a pivotal role in shaping energy economics by ensuring more predictable energy pricing structures. In countries where sharp turns in weather and extreme temperatures are observed, Underground Gas Storage comes out as the only viable, eco-friendly, and cost-effective specialized means of gas storage that could be set-up for trading purposes whenever the need arises.

The swift growth of natural gas production has seen Underground Gas Storage become an essential part of gas transmission systems. Additionally, it would be of greater value if these facilities existed close to areas that required the most attention in terms of heating and lighting through gas sources. Countries that import natural gas reserves in large amounts such as Germany, France, and Italy have to draw-up sound stratagems to set-up UGS establishments near to industrial and urban areas to meet their needs and also to get a steady supply and economical prices in their mid and long-term gas procurement contracts (Nacul et.al, 1997). UGS is a renowned technique put to practice by gas utilities, gas producers, and substantial end consumers simply due to its cost-effectiveness. Steady gas service to industries that need to work non-stop also benefit from this facility. (Omer et al., 2000).

2.7 Storage Natural Gas

Natural gas is produced from sub-surface formations in tandem with oil (associated gas) or without accompanying the production of oil i.e., just gas is produced (non-associated gas). Around 63% of US gas production is through non-associated gas reserves (EIA, 2019).

Natural gas mainly comprises of methane. It may contain higher hydrocarbon gases which include ethane, propane, butane, and pentane. The non-hydrocarbon gases usually present in methane include carbon dioxide, hydrogen sulphide, argon, nitrogen, and helium. Natural gas is often formed in porous sub-surface regions usually under immense pressure due to overburden arising from the overlying formations and sediments. When it is present in solution form with reservoir oil or condensate, it may be deemed as the vaporous content of that oil or condensate. Natural gas is predominantly put to use as a fuel for industrial concerns and undertakings as well as for fulfilling the residential area needs. Recently, a significant quantity of the produced natural gas is also being used as raw materials for processing in the chemical industries. If one were to adopt the storage facilities option for accumulation of natural gas, there would be a low number of production and transport plants that would be required for this case. The gas sale and other prices would also be lower. It would also result in prosperity of the society and country at large. This enterprise, however, requires huge amounts of capital investments and the ultimate gas operating price would be transferred to the customers. The total resulting price that is transferred from by adopting the storage process would still be lower than the traditional methods of handling gas production, transportation, and expensive storage options (Huo et al., 2021).

Natural gas storage kind of acts as a barrier or shield for the whole gas process from its production to its transmission. This ensures a steady energy supply, whenever needed, thereby saving costs that would have to be paid if the whole system were not stable. Electricity, on the other hand, can’t really be stored. Therefore, certain limits as to electricity generation are set up in the first place in order to avoid certain electricity losses through the transmission and distribution lines. Natural gas is storable in certain facilities as well as in pipelines which accounts for greater resistance from internal or external disturbances and inconveniences. This further accounts for greater security related to operations of the main working system in place. This security provided through storage facilities is proving immensely valuable, especially in exorbitant gas supply networks. This is subsequently leading to more lucrative business cases as the natural gas storage sector is relaxing its conditions for setting up said storage facilities. (Ki-Joong Kim et al., 2002)

2.8 Natural Gas Archives

The utilization of natural gas dates back to ancient China, where it was employed for various applications. Early Chinese engineers developed a rudimentary transportation system using bamboo shoots to transport natural gas from seepages. This transported gas was used to boil seawater, extracting valuable salts[1]. This marked the initial utilization of natural gas for practical purposes.

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[1] Natgas. (2013). *History of Underground Gas Storage*. http://Naturalgas.Org/Overview/History/.

In 1785, Britain became the first country to commercialize natural gas produced from coal, primarily for lighting houses and streetlights[1]. Around 1816, the United States began using synthetic gas produced from artificial processes for street lighting in Maryland, Baltimore. However, this synthetic gas was less cost-effective and eco-friendly than naturally occurring natural gas[1]

The United States witnessed significant developments in natural gas production. In approximately 1626, French pioneers noticed gases percolating and draining into Lake Erie, indicating the existence of natural gas in underground formations. The first dedicated well for natural gas production was drilled in 1821 by William Hart in Fredonia, New York, at a depth of 27 feet. This marked the beginning of natural gas production in the United States, and the industry began to grow. Colonel Edwin Drake drilled the first oil well in 1859, discovering naturally producible oil and natural gas during the process[2].

Throughout the 19th century, natural gas primarily served as a lighting source due to the absence of an efficient transportation infrastructure. The lack of a reliable framework made it challenging to transport gas to households for heating and cooking. In 1891, efforts were made to construct a natural gas pipeline structure stretching 120 miles from Central Indiana to Chicago. However, this early pipeline's transportation efficiency was hindered by its rudimentary design. Significant advancements in pipeline construction occurred during World War II, introducing improved welding techniques, curved pipe manufacturing, and metallurgical processes. These developments laid the groundwork for stable and efficient natural gas pipeline networks[3].

2.9 Impetus behind Natural Gas Storage

According to (Ozturk, 2004), the storage facility implementation has been widely successful in serving a number of operations in the past and is still being

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[2] Croft Systems. Natural Gas - Where It All Began. Retrieved from https://www.croftsystems.net/oil-gas-blog/natural-gas-where-it-all-began/

[3] Lebanon, Tennessee. History of Natural Gas. Retrieved from https://www.lebanontn.org/183/History-of-Natural-Gas

researched on for more ways in which it could be effectively used. Some rationale for employing UGS is as under:

- It dispenses an economical way for supply of gas to fulfil the objective of residential space heating (heating equipment used by people to fulfil heating needs)
- The transmission pipelines are subject to full usage whether gas is being supplied to end-consumers or being fed into the UGS reservoirs for the purpose of storing.
- Lowering the pressure level of wells during the busiest times to ensure effective and increased deliverability of gas.
- It can also act as a stand-by reserve for countries having large transmission networks. In-case of a pipeline failure, the gas supply could be stopped and fed back into the underground storage reservoir.
- It also substantially minimizes the risk of explosions and blowouts as the gas is stored in a zero-oxygen environment.

2.10 Different Natural Gas Storage Facilities

Most of the subsisting gas storage facilities are set up in exhausted natural gas and oil fields/wells that are situated close to various sectors that rely on a steady supply of a gas. (Güyagüler, 1998) This is advantageous in the sense that when a producing field is converted to serve as storage facility, there is already a pipeline network and different gathering systems in place. Furthermore, the geology, geography, and producing factors of the area/well are well known and properly documented which further aids personnel in determining what type of formation to expect in the sub-surface. This decision however depends on the right selection of depleted fields to be used as storage facility.

In some areas, aquifers are also being used as gas storage reservoirs. This is only possible if the rock formation encompassing the water aquifer has an impregnable cap rock seal. A seal is a rock structure that helps in restricting further migration of reservoir fluids. The geological features of the aquifer are somewhat similar to depleted gas production fields. It is a well-known fact that although the geology of aquifers is somewhat similar to producing fields that are depleted, it however requires some quantity of gas already present in it (cushion gas) to be used as a storage facility

(Güyagüler, 1998). It also requires vigilant assessment and evaluation of its gas withdrawal and injection figures. If the aquifer acts as an active water drive, the deliverability values of the produced or injected gas could increase.

Another type of geological feature and formation that could be used as a storage facility for preserving gas is Salt Caverns. They also provide viable rates of gas withdrawal and injection as well and their already in-place gas requirement i.e., cushion gas requirement is lower than that of aquifer systems. Most of the storage sites that have been developed in salt cavities are present in salt domes (Al-Shafi et al., 2023). A salt dome is basically a type of tectonic dome that is formed when overlying sediments are intruded by salt or different water-soluble minerals to constitute a process called diapiric. Salt caverns are drained and separated away from salt beds (which are usually more prone to deterioration and thinner in comparison) to give a resulting product that could store high volumes of a fluid and is more flexible to utilize. It is more expensive to construct gas storage facilities from salt caverns than it is to do from exhausted production fields. If we look at in terms of a relation i.e., dollars per thousand cubic feet of working gas (gas quantity that is present in a reservoir structure above the base gas quantity), salt cavern storage facility is expensive, but the greater deliverability rates provided by salt cavity gas storage facilities in each series throughout the year tends to decrease the per unit cost of every thousand cubic feet of gas injected and withdrawn from the said storage facility (Liu et al., 2023).

Storage sites may be categorized as those from whom sporadic and periodical gas supply requirements each year could be met i.e., exhausted gas fields and aquifer structures and those from whom continuous supply is needed all year round due to their high deliverability rates i.e., salt cavern formations. A depleted gas or oil well and aquifer could be modified to increase deliverability rates by increasing its overall porosity (number of empty spaces) and permeability (ability of fluid to flow). Another factor that may aid the process further would be the presence of high base (cushion) gas pressure and an optimal number of wells connected to the same reservoir to increase rate of withdrawal. It would also be preferable and expedient to a replenish the reservoir by injection in the least possible time. Salt caverns and cavities are comparatively better at exhibiting greater deliverability rates as this reservoir is fundamentally a huge pore space.

2.11 Exhausted Gas Fields (Depleted Fields)

According to (Tureyen et al., 2000), underground gas fields can be used for the purpose of constructing storage facilities if they have the desired and relevant porosity, permeability, and withholding capability. Mostly, all gas reservoirs share the same geologic characteristics in the sense that they have the same porous structure (usually greater) in order to store gas easily, however, they may have reduced permeability values that may primarily be due to the impermeable formations present above the main hydrocarbon-infused beds. Depleted Gas fields are usually converted and employed as storage sites due to their abundance in nature. In order to maximize efficiency of withdrawal performance, they use the pressure of stored gas and water drive of an aquifer. The cycling operations (number of times the gas is injected or withdrawn from relevant reservoir per year) are also comparatively lower for these reservoirs and the deliverability figures and values usually depend on the grade of porosity and permeability of the reservoir rock. Generally, natural gas storage facilities from depleted gas fields are designed in such a way to authorize one injection and one withdrawal operation per year (Öztürk, 2004).

The diurnal deliverability rates observed are mainly dependent on four important parameters which include type of surface facilities employed, cushion gas amount present in the reservoir, the fluid flow parameters, and lastly the retention capability (extent to which the reservoir can withhold fluids within it). This type of gas storage facility is also the most economical to construct, operate, and sustain. In order to use an abandoned gas field as a storage reservoir, one or more wells connected to the reservoir from which gas was produced are used to inject gas back into the reservoir. Generally, more porosity means more space for gas. However, as the reservoir pressure increases, more force would be required to inject gas further inside the reservoir. However, this high pressure would help in efficient and swift extraction and withdrawal of gas. In some areas where the reservoir rock is ‘tight’ due to overburden forces exhibited by overlying formations, some type of stimulation technique has to be employed to force cracks or fractures formation in the reservoir to aid better flow capability of hydrocarbons towards and up the well-bore (Al-Shafi et al., 2023).

Another important factor that must be assessed is the prompt guarantee of gas deliverability from storage facilities to different sectors as per the need arises, especially during times of high season. This is essentially a reference towards the coldest times of the year. At such conditions, it is expected that the storage sites would be able to deliver at least 50% or more of its original amount amassed in-place. This should occur in a span of 3-4 months. It is also for this reason that storage facilities need more wells for accumulating the gas than the actual number of wells present that were used during actual production operations of naturally occurring gas. Apart from this, studies should also be conducted at minimum and maximum pressure values to test the possibility of reservoir break-down due to continuous injection and withdrawal operations. They should be designed to handle stress levels that arise as a result of the constant cycles. The storage site should be handled with care so as to supply only the required amount of gas to the different sectors that need it (Tureyen et. al., 2000).

A comprehensive study along with different models of the storage reservoir would help in correctly assessing current needs and forecasting future needs so when such a time comes where the demand for gas is greater than the total production capacity of the live wells, it could easily be compensated by the gas present in storage facilities. This is how the total demand could be met, by replenishment with make-up gas (Güyagüler, 1998).

Another useful observation that could be made regarding underground gas storage in depleted gas wells is that its performance could be measured by the same graphs of gas production versus reservoir pressure that are used during actual live natural production of gas. A high pressure in the reservoir usually means that the maximum amount of gas is present in the reservoir. Therefore, to produce the gas at high pressures with considerably high flowrate is the basic aim of personnel handling storage facilities while designing the sites. (Al-Shafi et al., 2023).

2.12 Aquifer

Natural aquifers are considered suitable sites for the underground storage of natural gas when they are equipped with impermeable caprocks (Neumann and Zachmann, 2008). In such settings, the introduction of natural gas into the aquifer can systematically displace the formation water, thereby artificially generating storage capacity for the natural gas (Bencini, 2010). In contrast to the storage of natural gas within depleted hydrocarbon reservoirs, underground natural gas storage in aquifers demands a higher volume of cushion gas, sometimes reaching up to 80% of the total gas volume. Additionally, it necessitates meticulous monitoring of the performance of gas withdrawal and injection processes (Sunjay and Singh, 2010).

By the close of 2018, the global landscape boasted approximately 80 underground natural gas storage projects situated within aquifers, collectively referred to as UGSA (UGS in aquifers). These projects held a cumulative working gas capacity of 46.7 billion m³, representing roughly 11.9% of the worldwide UGS market. Predominantly, these initiatives were concentrated in countries such as the United States (51 projects), France (12 projects), Germany (8 projects), and Russia (7 projects). The inaugural UGSA endeavor in the United States, known as the Does Run Upper project, was established in 1976 and occupies a location straddling the border between Kentucky and Indiana (Cates, 2001). Meanwhile, the Herscher Galesville project, with a storage depth of approximately 536 meters and a working gas capacity of 0.378 billion m³, stands as the world's second UGSA and was constructed in Iowa. In France, UGSA initiatives are predominantly sited within the Paris Basin and Aquitaine Basin (Hugout, 1997). Among them, Beynes holds the distinction of being the first underground gas storage in an aquifer in France, with origins dating back to 1956. A more substantial endeavor, the Chemery gas storage facility, reigns as the largest UGSA in France, boasting an effective working gas capacity of 3.28 billion m³, and was commissioned in 1968. The burial depth of UGSAs in France spans from 405 meters to 1135 meters, encompassing a cumulative working gas volume of 11.43 billion m³. Russia's inaugural UGSA, Kalugskoe, was established in 1959, featuring gas injection at a depth of 800 meters and a working gas capacity of 410 million m³ (Yang et al., 2018). In Russia, the burial depth of seven UGSAs spans from 400 meters to 1050 meters.

2.13 Salt Formations

Underground gas storage (UGS) is a key technology for ensuring the security and reliability of natural gas supply. Salt caverns are the most common type of UGS facility. They are formed by injecting water into a salt formation, which dissolves the salt, creating a cavity (Zhang et al., 2022). Salt caverns are a safe and reliable way to store gas because salt is a stable material. It is not affected by weather or earthquakes, and it can withstand high pressures.

- Salt caverns are formed by injecting water into a salt formation at a pressure that is greater than the pressure of the salt.

- The water dissolves the salt, creating a cavity.
- The size of the cavity depends on the amount of water injected and the pressure of the water.
- Salt caverns can be used to store large volumes of gas.
- The capacity of a salt cavern depends on its size and the pressure of the gas.
- Salt caverns can be used to store gas for long periods of time, up to several years.
- Salt caverns are a safe and reliable way to store gas.
- They are not affected by weather or earthquakes.
- They can withstand high pressures.
- They are relatively inexpensive to construct and operate.

2.14 Cushion Gas

"The cushion gas may be native gas that has never been produced, or it may be injected gas that has been produced at some other location and injected into the reservoir." (Orin, 1995). Cushion gas, a fundamental component of UGS, is the inert gas that occupies the reservoir space in UGS facilities. Typically, natural gas reservoirs contain some amount of cushion gas to maintain the pressure needed for gas withdrawal. Nitrogen or carbon dioxide is often used as cushion gas due to their non-reactive properties. The primary purpose of cushion gas is to preserve the integrity of the reservoir, ensuring that the stored natural gas remains at the required pressure levels during extraction. This is essential for maintaining the operational efficiency and safety of UGS facilities.

Cushion gas plays a crucial role in the cycling process of UGS facilities. During the injection phase, surplus natural gas is injected into the reservoir, displacing the cushion gas and increasing the reservoir pressure. Conversely, during withdrawal, the stored gas is extracted, and cushion gas is injected to maintain the reservoir's pressure. This cycling of cushion gas is a dynamic process that allows UGS facilities to respond swiftly to changes in energy demand. It provides operational flexibility, enabling gas utilities to balance supply and demand effectively (Flanigan, 1995).

Efficient management of cushion gas is vital for optimizing the performance and cost-effectiveness of UGS operations. The volume and composition of cushion gas can significantly impact the deliverability and capacity of an underground storage facility.

Therefore, gas operators carefully monitor and control cushion gas injection and withdrawal rates to ensure operational stability. Effective cushion gas management also contributes to energy security by enhancing the reliability and responsiveness of UGS facilities, especially during periods of peak demand or supply disruptions (Fabbi et al., 2023)

2.15 Working Gas

Working gas is the volume of gas in an UGS facility that is available for withdrawal. It is calculated by subtracting the cushion gas volume from the total gas volume in the facility. The cushion gas volume is the volume of gas that is used to maintain the pressure in the facility and prevent it from collapsing.

"Working gas is the volume of gas in an underground gas storage facility that is available for withdrawal. It is calculated by subtracting the cushion gas volume from the total gas volume in the facility" (International Gas Union, 2003).

The working gas volume in an UGS facility can vary depending on the time of year, the demand for gas, and the availability of gas from other sources. During periods of peak demand, the working gas volume may be reduced to a minimum level. During periods of low demand, the working gas volume may be increased to a maximum level.

The working gas volume in an underground gas storage facility can vary depending on the time of year, the demand for gas, and the availability of gas from other sources[4]

The working gas volume is an important factor in the operation of an UGS facility. It must be carefully managed to ensure that the facility is operated safely and efficiently.

2.16 Research Gap

This research is based on addressing three areas in literature where existing body of knowledge is lacking.

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[4] U.S. Energy Information Administration. (2015). Natural Gas Storage. Retrieved from https://www.eia.gov/naturalgas/storage/basics/

1. **Energy Security in Pakistan**: While extensive research has been conducted on energy security, there's a research gap in comprehensively analysing the multifaceted dimensions of energy security specific to Pakistan. Existing studies tend to focus on global or regional contexts, leaving a need for research that delves deeper into Pakistan's unique challenges and opportunities in achieving energy security.
2. **Techno-Commercial Evaluation of UGS in Pakistan**: There is a research gap in conducting a comprehensive techno-commercial evaluation of UGS in Pakistan. Existing literature lacks in-depth analyses of the economic viability of UGS projects in Pakistan's specific geological and market conditions. Bridging this gap can provide valuable insights into the feasibility of UGS as an energy security solution in the country.
3. **Optimization of UGS in Pakistan:** While optimization techniques for UGS facilities are well-established, there exists a research gap in their application and customization to Pakistan's energy landscape. Investigating how optimization methods can be tailored to the country's unique challenges, such as varying demand patterns and geological constraints, is essential for enhancing energy security through UGS.

2.17 Research Questions

Following are the questions of this research:

1. How is Energy Security of Pakistan performing using 4 A’ framework?
2. Is UGS Technically feasible in Pakistan?
3. How UGS can be optimized using Linear Programming Method?

Chapter 3. RESEARCH METHODOLOGY

3.1 Research Paradigm

In the research methodology chapter of this thesis, the chosen research paradigm serves as the overarching framework that guides the approach and perspective adopted to address the research objectives. The research paradigm selected for this study is rooted in the positivist tradition, emphasizing a quantitative and empirical approach to investigate the optimization of gas management through UGS facilities. This paradigm aligns with the study's aim to analyse and model complex systems, employing systematic and measurable techniques to enhance energy security.

Within the positivist paradigm, a deductive research approach is employed, whereby hypotheses are formulated based on existing theories and concepts within the fields of energy security, reservoir engineering, and optimization algorithms. This deductive reasoning allows for the systematic testing of hypotheses through rigorous data collection and analysis. Quantitative data, such as reservoir properties, historical energy consumption patterns, and cost variables, will be collected to provide a factual foundation for analysis.

Furthermore, the research design falls under the category of explanatory and applied research, as it seeks to understand and explain the relationships between variables by identifying patterns and causal factors affecting the optimization of gas management systems. By employing mathematical models to simulate underground gas storage behaviour and employing linear programming algorithms to optimize resource allocation, this research aims to uncover the underlying mechanisms driving energy security enhancement through the utilization of depleted reservoirs. The research paradigm, characterized by its positivist, deductive, and explanatory nature, provides a robust and systematic framework to explore the intricate dynamics of underground gas storage optimization within the context of energy security in Pakistan.

3.2 Research Settings

In this section, the environment, circumstances, sampling rationale and other important factors that were considered in designing the research as well as gathering data, will be discussed.

3.2.1 Research Setting for Qualitative Study

The qualitative study utilizing the 4As methodology is set in the context of Pakistan (Malik et al., 2020), relying on data extracted from the Energy Year Book of Pakistan for the fiscal year 2019-20. This research seeks to comprehensively explore and understand energy security within the unique socio-economic and geographical landscape of Pakistan. The study incorporates a documentary analysis approach, making use of publicly available reports, data, and records from authoritative sources.

The geographical focus of this research encompasses a selection of regions across Pakistan. This deliberate choice aims to capture the diversity of Pakistan's energy landscape, including urban and rural areas. The selected regions serve as representative case studies for examining energy security challenges and opportunities. By considering a variety of geographical contexts, the study aims to provide a nuanced understanding of how energy security dimensions manifest in different parts of the country.

While the research draws on data from the Energy Year Book 2019-20, it does not involve direct interviews or interactions with individuals or organizations. Instead, it relies on a systematic analysis of existing documents and records to uncover insights related to the four dimensions of energy security outlined in the 4As methodology: Availability, Applicability, Acceptability, and Affordability. This methodological approach enables a comprehensive exploration of energy security in Pakistan, contributing to a holistic understanding of the nation's energy landscape and challenges. Ethical considerations and data privacy guidelines are upheld throughout the study to ensure the responsible use of publicly available information.

3.2.2 Research Setting for Analytical Study & Selection of Case Field

Depleted Case field data from Badin (South Of Pakistan) serves as a crucial element in the research's quantitative modelling of UGS facilities. Extracted from geological records and previous extraction activities, this data provides insights into reservoir properties such as porosity, permeability, and historical gas composition. Employing this data within specialized reservoir simulation software, the modelling process aims to simulate the behaviour of UGS and withdrawals. The integration of this data into reservoir models facilitates the prediction of gas injection and withdrawal rates, enabling the optimization of storage strategies and energy resource utilization.

To address the optimization aspect, the research leverages the Python programming language, specifically utilizing the PuLP library, to implement linear programming algorithms. Python's versatility and PuLP's optimization capabilities enable the formulation of mathematical models that consider various constraints, objectives, and decision variables. By applying this technology to the estimated energy security levels and the modelled gas storage dynamics, the research aims to identify optimal scenarios that enhance energy security while accounting for multiple factors simultaneously. The utilization of Python and PuLP in the optimization process ensures a systematic and efficient approach to resource allocation, contributing to the overall methodology's robustness and effectiveness.

In summary, the research settings of this quantitative study draw on a combination of authoritative data from the Energy Yearbook, detailed reservoir data from the depleted X field, and the computational power of Python with the PuLP library. These settings collectively facilitate the holistic assessment of Pakistan's energy security using the 4A methodology, as well as the modelling of UGS behaviour and the optimization of resource allocation to strengthen energy security.

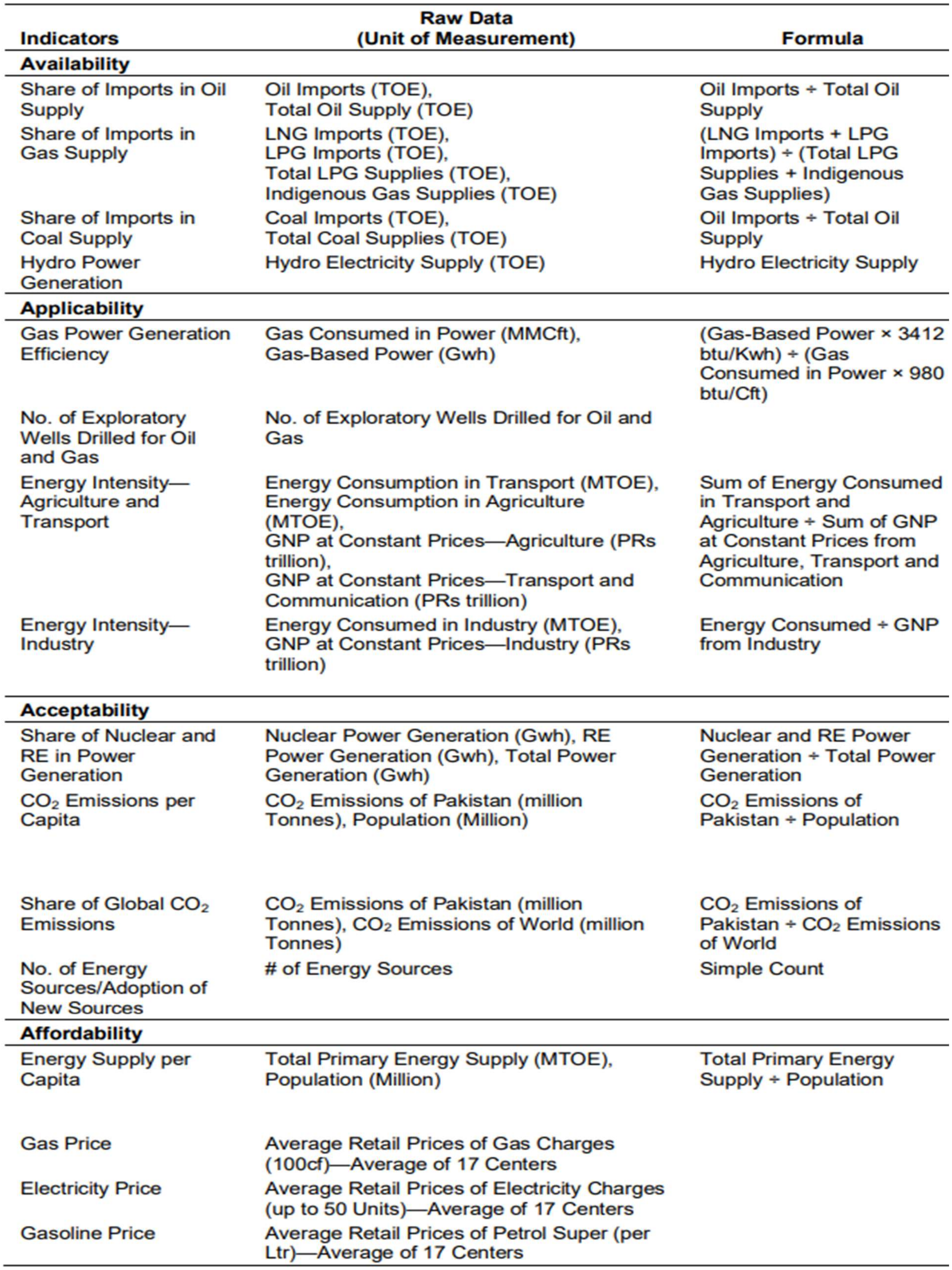
3.3 Research Method/Design

The research has three phases. How methods and design of these parts have been worked out is discussed in this section. Following are the phases of research:

Phase-1: 4 A’s Estimation
Phase-2: Technical Feasibility of UGS by using MBAL Software
Phase-3: Python Code for Optimizing Storage and evaluating Break Even Cost using Linear Programming Method.

3.3.1 Phase-1: 4 A’s Estimation

In order to finalize the technique for conducting qualitative part of this research, extensive literature review was carried out. The relevant research articles were studied with respect to the survey.



Indicators	Raw Data (Unit of Measurement)	Formula
Availability		
Share of Imports in Oil Supply	Oil Imports (TOE), Total Oil Supply (TOE)	Oil Imports ÷ Total Oil Supply
Share of Imports in Gas Supply	LNG Imports (TOE), LPG Imports (TOE), Total LPG Supplies (TOE), Indigenous Gas Supplies (TOE)	(LNG Imports + LPG Imports) ÷ (Total LPG Supplies + Indigenous Gas Supplies)
Share of Imports in Coal Supply	Coal Imports (TOE), Total Coal Supplies (TOE)	Oil Imports ÷ Total Oil Supply
Hydro Power Generation	Hydro Electricity Supply (TOE)	Hydro Electricity Supply
Applicability		
Gas Power Generation Efficiency	Gas Consumed in Power (MMCft), Gas-Based Power (Gwh)	(Gas-Based Power × 3412 btu/Kwh) ÷ (Gas Consumed in Power × 980 btu/Cft)
No. of Exploratory Wells Drilled for Oil and Gas	No. of Exploratory Wells Drilled for Oil and Gas	
Energy Intensity—Agriculture and Transport	Energy Consumption in Transport (MTOE), Energy Consumption in Agriculture (MTOE), GNP at Constant Prices—Agriculture (PRs trillion), GNP at Constant Prices—Transport and Communication (PRs trillion)	Sum of Energy Consumed in Transport and Agriculture ÷ Sum of GNP at Constant Prices from Agriculture, Transport and Communication
Energy Intensity—Industry	Energy Consumed in Industry (MTOE), GNP at Constant Prices—Industry (PRs trillion)	Energy Consumed ÷ GNP from Industry
Acceptability		
Share of Nuclear and RE in Power Generation	Nuclear Power Generation (Gwh), RE Power Generation (Gwh), Total Power Generation (Gwh)	Nuclear and RE Power Generation ÷ Total Power Generation
CO_2 Emissions per Capita	CO_2 Emissions of Pakistan (million Tonnes), Population (Million)	CO_2 Emissions of Pakistan ÷ Population
Share of Global CO_2 Emissions	CO_2 Emissions of Pakistan (million Tonnes), CO_2 Emissions of World (million Tonnes)	CO_2 Emissions of Pakistan ÷ CO_2 Emissions of World
No. of Energy Sources/Adoption of New Sources	# of Energy Sources	Simple Count
Affordability		
Energy Supply per Capita	Total Primary Energy Supply (MTOE), Population (Million)	Total Primary Energy Supply ÷ Population
Gas Price	Average Retail Prices of Gas Charges (100cf)—Average of 17 Centers	
Electricity Price	Average Retail Prices of Electricity Charges (up to 50 Units)—Average of 17 Centers	
Gasoline Price	Average Retail Prices of Petrol Super (per Ltr)—Average of 17 Centers	

Table-3-1 Energy Security Estimations (Malik et al., 2020)

3.3.1.1 Data Source

All the data required for estimation of Availability is taken from Energy Yearbook of Pakistan 2019-20. For the estimation of applicability Gas Power Generation Efficiency, No. of Exploratory Wells drilled and Energy Intensity - Agriculture & Transport is taken from Energy Yearbook 2019-20 whereas Energy intensity- industry is taken from Pakistan Economic Survey 2022.

For the estimation of Acceptability, share of Nuclear and RE in Power Generation is taken from Energy Yearbook of Pakistan 2019-20 whereas rest of the data is taken from British Petroleum Statistical Review of World Energy 2022. For the estimation of Affordability, Energy Supply per capita is taken from Pakistan Energy Yearbook 2019-20 whereas rest of the Data is taken from Pakistan Economic Survey 2022.

3.3.1.2 Data Transformation

To facilitate the comparison and interpretation of indicator values, the study employed a data transformation method that normalized the indicators onto a scale ranging from 1 to 10. This transformation allowed for a standardized assessment of the progress made for each indicator, aiding in a more comprehensive analysis.

The formula used for this normalization is as follows:

For indicators with a direct relationship to the scale

$$X' = 1 + ((X - \text{Min } X) / (\text{Max } X - \text{Min } X)) \times (10 - 1)$$

Where

X' Transformed indicator value

X Untransformed indicator value

Min X Minimum value of the indicator

Max X Maximum value of the indicator

For indicators with an inverse relationship to the scale

$$X' = 1 + ((\text{Max } X - X) / (\text{Max } X - \text{Min } X)) \times (10 - 1)$$

In the case of indicators that are inversely related to the scale, a higher value corresponds to lower energy security. Therefore, the formula has been adjusted to reflect this inverse relationship. By considering the maximum value of the raw score as the minimum scale value of the indicator (1) and converting the minimum raw score into the maximum value on the scale (10), the transformation accurately represents the indicator's significance.

It is important to note that while the scale facilitates easy comparison, it measures performance relative to the specific data range used to derive the indicators. Consequently, interpretation should be conducted cautiously, especially when small changes are observed. The scale's sensitivity to changes warrants a comprehensive assessment in conjunction with an understanding of the untransformed values and the data range characteristics.

By applying this data transformation method, the study ensured standardized indicators that could be interpreted within a consistent and understandable framework, contributing to a more insightful analysis of energy security dimensions.

3.3.2 Phase-2: Technical Feasibility of UGS by using MBAL Software

Technical feasibility is carried out based on the X Field located in the Southern part of Pakistan. Data from this is incorporated into Petroleum Specialized softwares MBAL and PROSPER to achieve Analytical Modelling results. Below are the modelling steps:

Step-1: Introduction to Well and Gas Storage Modelling

Well and UGS modelling is a cornerstone of energy system optimization. These models simulate well and storage reservoir behaviours, enabling strategic resource management for heightened energy security and sustainability.

Step-2: Selection of Modelling Software

The selection of modelling software involves a careful evaluation of features. Tools should possess advanced capabilities in reservoir simulation and wellbore modelling to accurately replicate complex fluid interactions. For this modelling, Petroleum Expert software is used. Module of software that are specifically related to the designing of underground storage is MBAL and PROSPER.

Step-3: Data Collection for Well Modelling

The accuracy of well modelling hinges on meticulous data collection. Key parameters, including well geometry, reservoir permeability, fluid properties, and initial pressures, are gathered to ensure precise simulation outcomes.

Step-4: Formation Pressure Drop Equation

The equation for formation pressure drop captures the impact of fluid flow within the reservoir matrix. It takes into account factors such as flow rate (q), permeability (k), height (h), and radial distances (r1 and r2) from the wellbore. This equation, derived from Darcy's law, serves as a fundamental tool in understanding pressure dynamics in the formation.

$$\Delta P\_formation = (q / (2 * \pi * k * h)) * ln((r1 + r2) / r1)$$

The logarithmic term accounts for radial flow behaviour around the wellbore, allowing for accurate pressure drop estimation.

Step-5: Wellbore Pressure Drop Equation

The equation for wellbore pressure drop is an essential component in assessing frictional losses along the wellbore. Factors such as the friction factor (f), fluid density (ρ), well length (L), flow rate (q), well diameter (D), and cross-sectional area (A) collectively influence the magnitude of pressure loss. The equation enables the quantification of energy losses that occur due to fluid flow friction within the wellbore.

$$\Delta P\_wellbore = (f * \rho * L * q\hat{}2) / (2 * D * A\hat{}2)$$

Step-6: Total Pressure Drop Equation

The total pressure drop equation represents the cumulative impact of both formation and wellbore pressure drops. By combining these two components, the equation provides a comprehensive insight into the overall pressure losses experienced by the fluid as it traverses the wellbore and the reservoir.

$$\Delta P\_total = \Delta P\_formation + \Delta P\_wellbore$$

Step-7: Well Productivity Equation

The well productivity equation establishes a critical link between production rate, total pressure drops (ΔP_total), and wellhead pressure (P_wh). It is a fundamental tool for assessing the well's capacity to deliver fluids at a given pressure.

$$\text{Productivity} = q / (\Delta P\_total + P\_wh)$$

Step-8: Bottomhole Pressure Equation

The calculation of bottomhole pressure (P_bh) is derived from the wellhead pressure (P_wh) and the total pressure drop (ΔP_total). This equation provides insights into the pressure conditions prevailing at the bottom of the well, contributing to a comprehensive understanding of the well's performance.

$$P\_bh = P\_wh - \Delta P\_total$$

Step-9: Skin Factor and Well Damage Analysis

The concept of skin factor represents the departure of actual well performance from ideal conditions. Positive skin factors indicate damage or reduced productivity, while negative values suggest enhanced productivity. Skin factor accounts for factors such as formation damage, perforation efficiency, and well completion effects.

Step-10: Gas Storage Reservoir Modelling

The gas storage reservoir modelling entails a detailed consideration of parameters like porosity, compressibility, and permeability. These parameters collectively dictate the behaviour of the gas within the storage reservoir.

Step-11: Material Balance Equation

The material balance equation is a cornerstone of gas storage reservoir modelling. By tracking the changes in gas volume over time, the equation quantifies the difference between the injected gas (Q_inj) and the produced gas (Q_prod), offering insights into storage dynamics.

$$\Delta V = Q\_inj - Q\_prod$$

Step-12: Pressure Change Equation

The equation for pressure change within the reservoir due to gas injection and production is a key determinant of reservoir performance. It factors in variables such as volume change (ΔV), compressibility factor (Z), gas constant (R), temperature (T), reservoir volume (V), and reservoir pressure (P).

$$\Delta P\_reservoir = (\Delta V * Z * R * T) / (V * P)$$

Step-13: Wellbore Behaviour and Pressure Transients

This section delves into the intricate behaviour of the wellbore during pressure transients, encompassing the effects of changes in injection and production rates on pressure dynamics. These transient behaviours contribute to a comprehensive understanding of the well's response to varying operational conditions.

Step-14: Gas Storage Efficiency Metrics

The metrics of deliverability, capacity, and pressure maintenance hold pivotal roles in assessing the efficiency of gas storage systems. Deliverability quantifies the rate at which gas can be withdrawn from storage, capacity denotes the maximum storage volume, and pressure maintenance reflects the reservoir's ability to maintain pressure levels over time.

Step-15: Validation and Calibration

The validation phase involves a rigorous comparison of modelling results with real-world field data, ensuring the accuracy of the simulation. Calibration techniques, such as adjusting model parameters, are implemented to enhance the alignment between model predictions and actual performance.

3.3.3 Phase-3: Optimization of Gas Procurement and Breakeven Cost Calculation

Step-1: Problem Definition

The primary objective of this methodology is to optimize the procurement strategy for a 7-month period while considering fluctuating gas prices and storage limitations. Additionally, it aims to estimate the breakeven cost of the produced gas, contributing to effective decision-making in gas procurement and production scenarios.

Step-2: Linear Programming (LP) Formulation

Linear Programming is a mathematical approach chosen for its ability to handle optimization problems with linear constraints and linear objective functions. It allows us to determine the optimal procurement plan by minimizing the total cost subject to various constraints.

Step-3: Objective Function

The central objective is to minimize the total cost of gas procurement over the 7-month horizon. Mathematically, the objective function is defined as

Minimize ∑ gas_prices[i] * procurement_vars[i]

This equation calculates the sum of products of gas prices and the corresponding procurement quantities for each month.

Step-4: Decision Variables

The decision variables **procurement_vars[i]** represent the amount of gas to be procured during month **i**. To ensure feasible solutions, these variables are constrained to lie between 0 BCF (no procurement) and 8 BCF (maximum procurement allowed).

Step-5: Constraints

Several constraints are imposed to ensure the validity of the solution

- **0 ≤ procurement_vars[i] ≤ 8** for each month **i**.
- **∑ procurement_vars[i] = 40** to ensure that the total gas procured over the 7-month period is equal to the storage capacity of 40 BCF.
- Non-negativity constraints are also imposed on each month's procurement **procurement_vars[i] ≥ 0** for each month **i**.

Step-6: Solution Process

The formulated LP problem is solved using an LP solver, which aims to find the values of decision variables that minimize the objective function while satisfying the defined constraints. The solver employs various mathematical techniques to optimize the solution and determine the optimal procurement plan.

Step-7: Breakeven Cost Estimation

The breakeven cost of produced gas is a critical metric for assessing economic feasibility. The estimation involves several steps

- Calculate **X = Total Injection Cost / 152**, where 152 represents the total gas procurement over 7 months (40 BCF).
- Compute **Y = X * 1000 / 250**, where 1000 converts BCF to MMBTU and 250 is the production rate in MMSCFD.
- The breakeven cost of produced gas equals **Y**, indicating the gas cost at which injection cost matches produced gas cost.

Step:8: Implementation and Validation

The Python programming language, along with the pulp library, is employed to implement the LP model. This implementation ensures accurate and efficient solving of the optimization problem. The results are validated by confirming that the optimized solution adheres to the defined constraints and produces the minimum objective function value.

Step-9: Interpretation of Results

The optimal procurement plan obtained from the LP solution provides insights into the recommended quantities of gas to be procured in each month. This plan minimizes costs while considering storage and procurement constraints. The breakeven cost offers additional insights by indicating the cost at which the investment in gas production becomes balanced with the procurement cost.

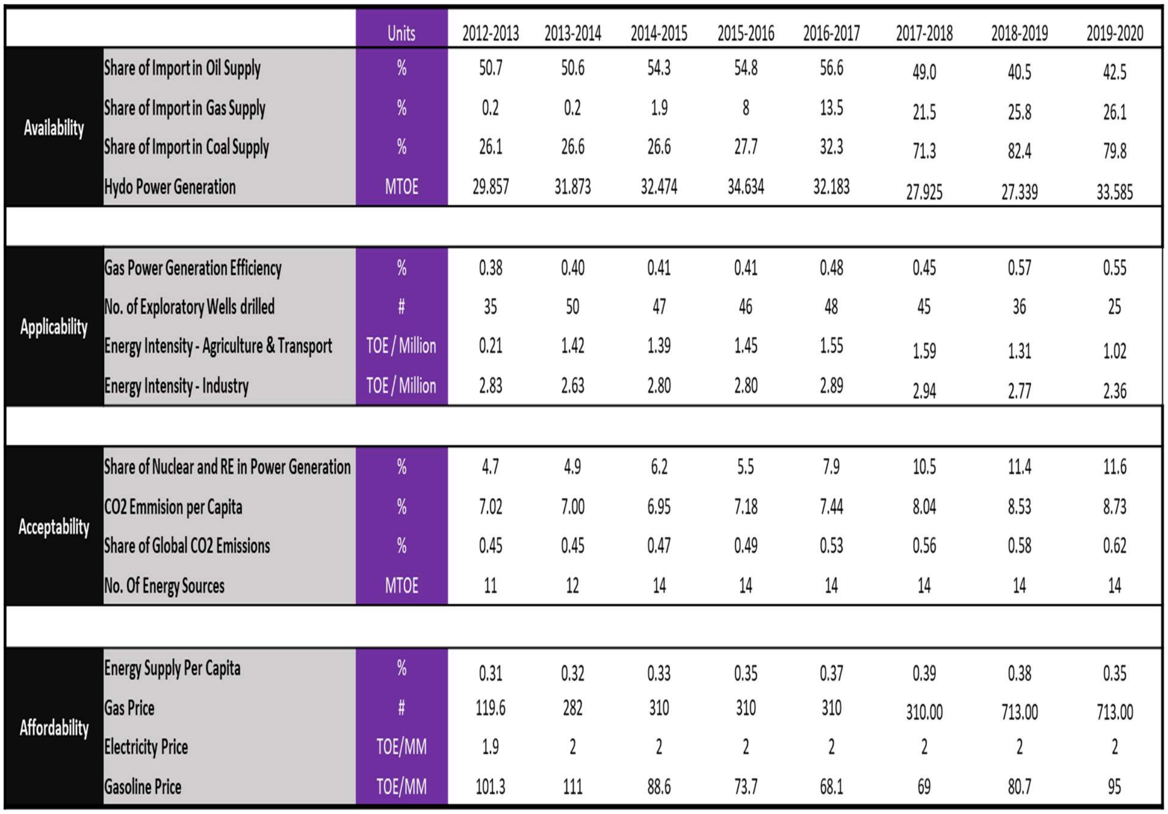
Optimization Model is run on 2022 data of Pakistan LNG Import through Qatar deal and Spot deal and results are in the appendices. Results show that there is $434 Million savings if optimizer is used and gas is procured during the months when prices were lower.

Chapter 4. RESULTS & DISCUSSION

The results of 4 A methodology are discussed in this section.

4.1 4A's Qualitative Analysis Results

All 4 A's results from 2011 to 2020 are compiled in the table below



		Units	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
Availability	Share of Import in Oil Supply	%	50.7	50.6	54.3	54.8	56.6	49.0	40.5	42.5
	Share of Import in Gas Supply	%	0.2	0.2	1.9	8	13.5	21.5	25.8	26.1
	Share of Import in Coal Supply	%	26.1	26.6	26.6	27.7	32.3	71.3	82.4	79.8
	Hydo Power Generation	MTOE	29.857	31.873	32.474	34.634	32.183	27.925	27.339	33.585
Applicability	Gas Power Generation Efficiency	%	0.38	0.40	0.41	0.41	0.48	0.45	0.57	0.55
	No. of Exploratory Wells drilled	#	35	50	47	46	48	45	36	25
	Energy Intensity - Agriculture & Transport	TOE / Million	0.21	1.42	1.39	1.45	1.55	1.59	1.31	1.02
	Energy Intensity - Industry	TOE / Million	2.83	2.63	2.80	2.80	2.89	2.94	2.77	2.36
Acceptability	Share of Nuclear and RE in Power Generation	%	4.7	4.9	6.2	5.5	7.9	10.5	11.4	11.6
	CO2 Emmision per Capita	%	7.02	7.00	6.95	7.18	7.44	8.04	8.53	8.73
	Share of Global CO2 Emissions	%	0.45	0.45	0.47	0.49	0.53	0.56	0.58	0.62
	No. Of Energy Sources	MTOE	11	12	14	14	14	14	14	14
Affordability	Energy Supply Per Capita	%	0.31	0.32	0.33	0.35	0.37	0.39	0.38	0.35
	Gas Price	#	119.6	282	310	310	310	310.00	713.00	713.00
	Electricity Price	TOE/MM	1.9	2	2	2	2	2	2	2
	Gasoline Price	TOE/MM	101.3	111	88.6	73.7	68.1	69	80.7	95

Table 4-1 4A's result compilation

Above compiled data shows that Pakistan is now heavily relying on the imported energy to meet its energy requirements. With provision of LNG imports from 2015, Pakistan's LNG import as significantly improved upto 26%. Interesting import of coal is also increasing due to the installation of Coal Power Plants for Power Generation. There is increase in Gas Prices from 2018 onwards but these Gas Prices are average price of all slabs. Minimum Gas Prices are not changed for domestic customers and same is the case with electricity customers.

4.2 Transformation of Data

This data is then transformed on a scale of 1-10. Transformed data is compiled in the table below for further interpretation.

	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20
Availability	7.1	7.7	7.2	7.3	5.6	3.1	3.3	5.0
Applicability	3.7	6.5	7.0	6.9	8.5	8.2	7.6	4.3
Acceptability	5.4	6.3	8.0	7.2	7.0	6.8	6.1	5.5
Affordability	6.0	2.8	4.2	5.4	6.3	7.0	4.3	3.0

Table 4-2 Data Transformation

Transformed data is showing continuous decrease in the availability of energy sources as there is continuously increase in the imports of Energy Sources, where as applicability is showing downwards trend due to the shrinkage of economy in 2016 onwards. Acceptability is also showing decreasing trend due to the increase of CO2 emissions due to the increase of Coal usage for the Power Generation Sector. Affordability is also showing decreasing trend as increase in fuel prices for the end consumers. Circular debt in power sector was increasing and its impact was not transferred to the consumers. There are many slabs for Gas and Electricity consumers and only average of those slabs were used in this study.

4.3 Availability

This parameter is calculated from Share of Import in Oil Supply, Gas Supply, Coal Supply and Hydropower Generation. As per results, availability if energy is decreasing during last 10 years. Import of LNG, shutting down of electricity generation from Furnace Oil Plants and installation of Imported Coal Power Plants. Addition of Renewable Energy sources like Solar, wind and nuclear plants has no significant contribution in improving the Energy Availability in the country.

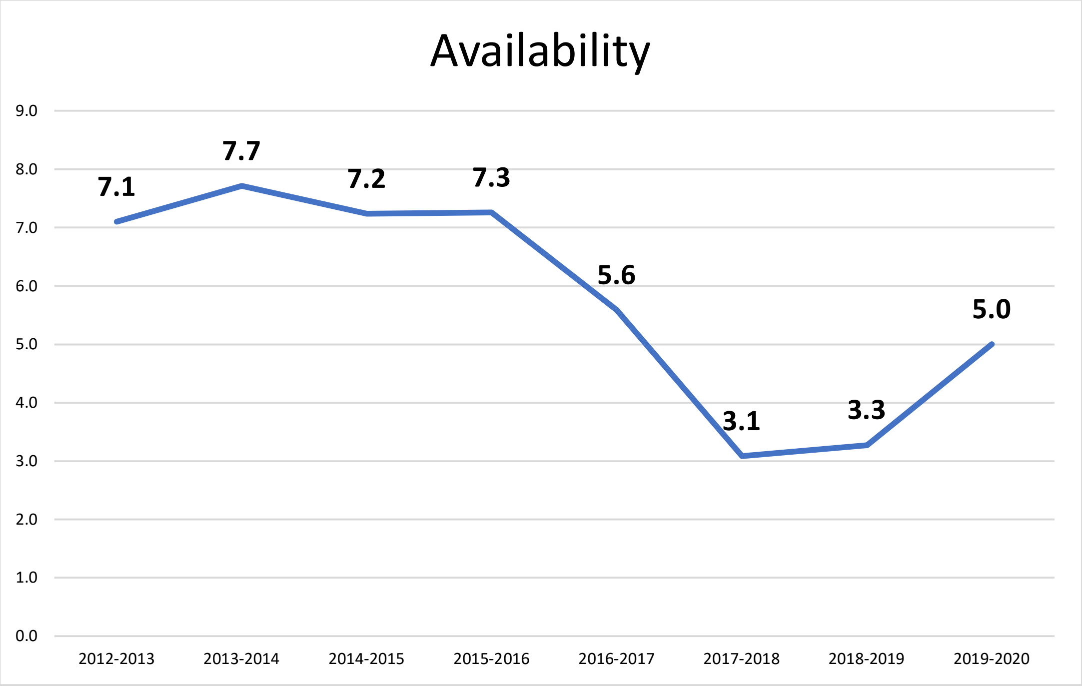


Figure 4-1 Availability Trend

Energy availability in Pakistan, scrutinized through the prism of the 4As methodology, unveils a significant dependence on imported energy resources. The share of energy imports in oil, gas, and coal supplies emphasizes the nation's vulnerability to international market fluctuations and supply disruptions. This highlights the imperative to fortify domestic energy sources, enhance energy exploration, and strategically utilize indigenous reserves. By leveraging diversified energy portfolios and optimizing resource allocation, Pakistan can mitigate the risks associated with overreliance on imports, bolstering its energy security and contributing to a stable and resilient energy landscape.

4.4 Applicability

The applicability is showing upside trend from 2013 onwards as number of exploration activities were higher during this time. After 2019, country was going to economic slowdown, and it contributed to the decrease of energy applicability.

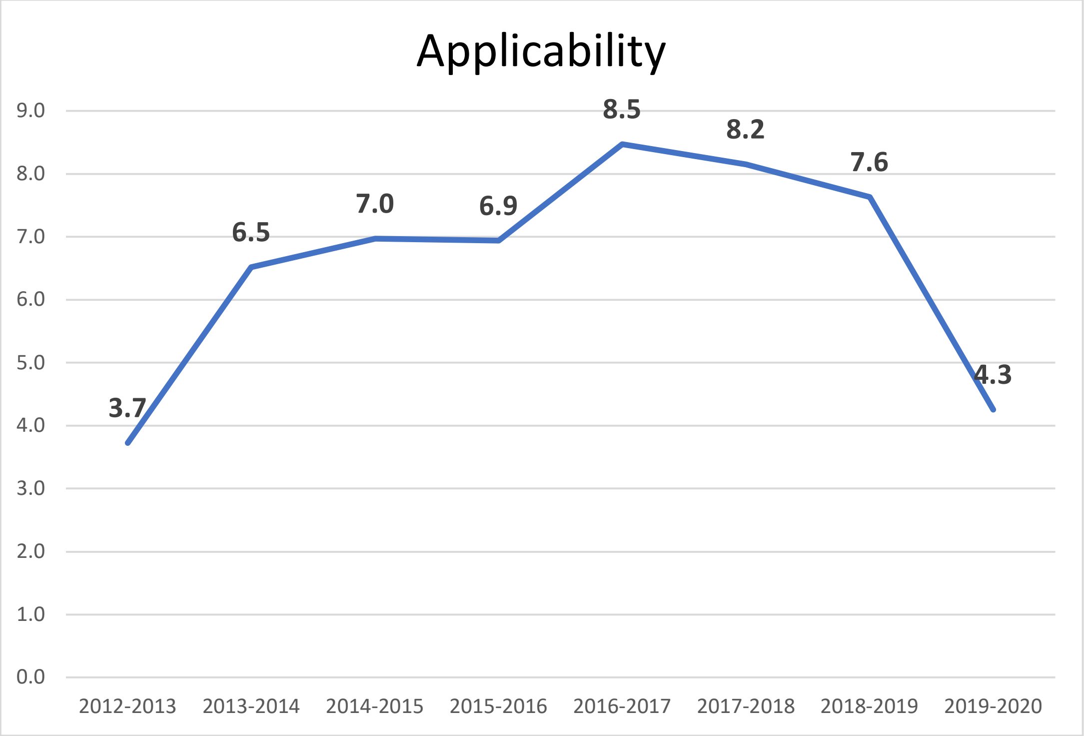


Figure 4-2 Applicability Trend

Energy applicability in Pakistan, analysed within the framework of the 4As methodology, illuminates the country's potential to harness a diverse array of energy sources. The assessment of hydro power generation and gas power generation efficiency underscores the opportunity to tap into renewable and efficient energy technologies. Pakistan's abundant water resources enable the development of hydroelectric power, offering a sustainable and climate-friendly energy solution. Furthermore, improving the efficiency of gas power generation can optimize the utilization of natural gas resources, a crucial asset for the country. Embracing these applicable energy sources aligns with Pakistan's sustainable development goals, promoting energy resilience, environmental protection, and technological advancement for a more secure energy future.

4.5 Acceptability

Acceptability is estimated Share of Nuclear and RE in Power Generation, CO2 Emission per Capita, Share of Global CO2 Emissions and No. Of Energy Sources. During last 10 years there is increase in investment on Nuclear and RE projects which has contributed to lower CO_2 emissions. This all resulted in significant improvement in the acceptability of Energy in Pakistan.

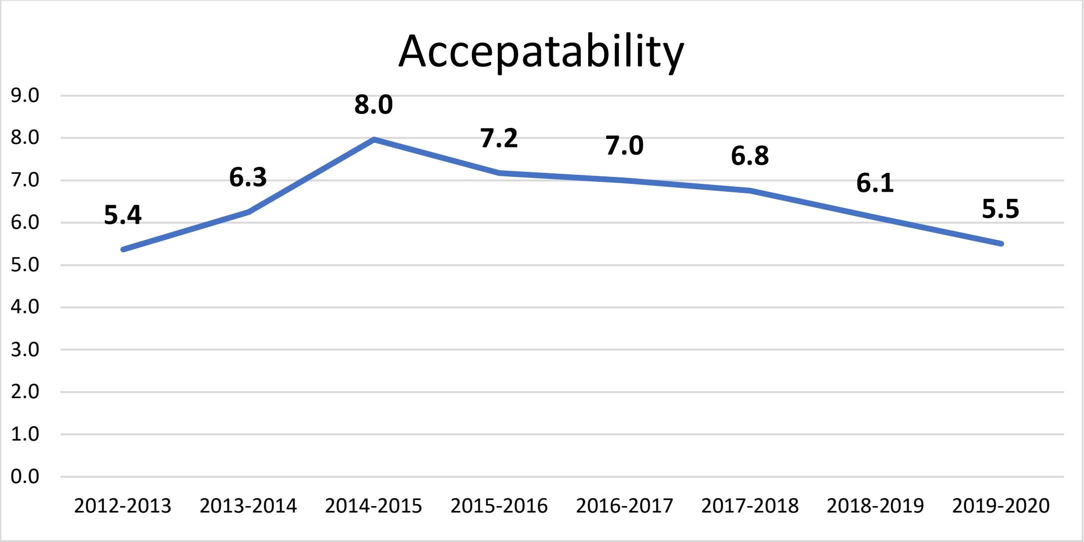


Figure 4-3 Acceptability Trend

Energy acceptability in Pakistan, evaluated through the lens of the 4As methodology, underscores the importance of diversifying the energy mix to align with environmental and societal concerns. The share of nuclear and renewable energy in total power generation signifies the nation's strides toward cleaner and more sustainable energy sources. Embracing nuclear and renewable options not only reduces carbon emissions but also addresses growing environmental apprehensions. Additionally, by enhancing public awareness and fostering acceptance of these alternatives, Pakistan can foster a balanced energy ecosystem that meets both energy security imperatives and the expectations of a society increasingly committed to preserving the environment and minimizing ecological impact.

4.6 Affordability

Energy affordability interesting showing decrease in affordability but there are certain assumptions. Electricity prices in Pakistan are different in sector for the Residential and Commercial consumers, same is with the Gas Prices. In this 4A methodology, minimum price of electricity is taken which hasn't changed during last 10 year. For Gas prices average of price range is taken which shows increase during last 2 years.

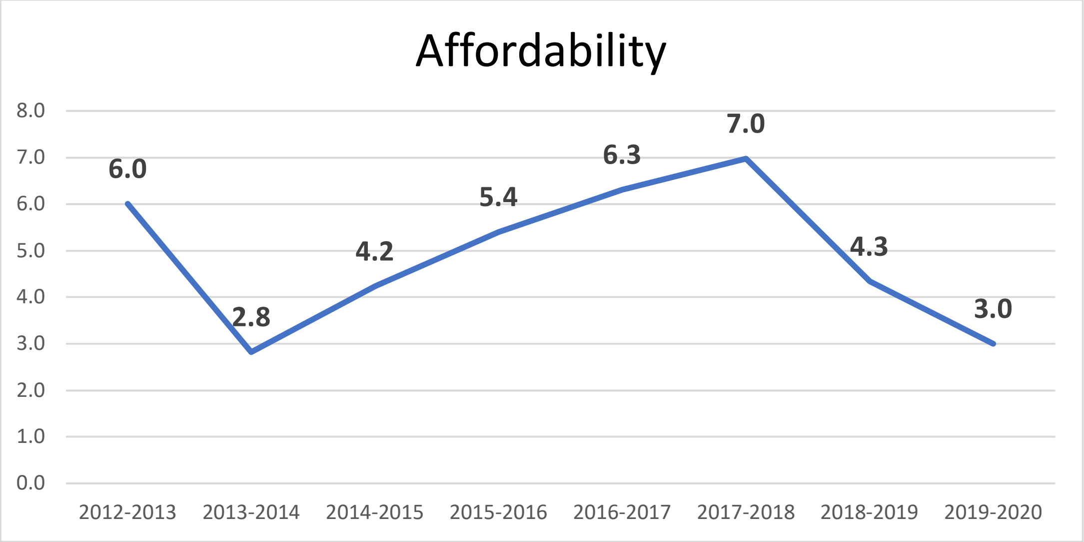


Figure 4-4 Affordability Trend

Energy affordability in Pakistan, assessed through the prism of the 4As methodology, is a critical consideration in ensuring equitable access to energy resources. The analysis of energy supply per capita and fuel prices reflects the intricate balance between meeting energy demands and economic feasibility. As Pakistan aspires to uplift its population and economy, it is imperative to provide affordable energy options that support sustainable growth while safeguarding consumer welfare. By implementing effective energy pricing strategies, subsidies for vulnerable populations, and promoting energy-efficient technologies, Pakistan can enhance energy accessibility without compromising economic stability, ultimately contributing to a more inclusive and resilient energy landscape.

Figure 4-5 Web Plot of the Energy Security of Pakistan years wise

4.7 Underground Storage Modelling

In figures 4-1 history matching results shows that model is validated. The Pressure and Production History of actual field is matching with Model's history

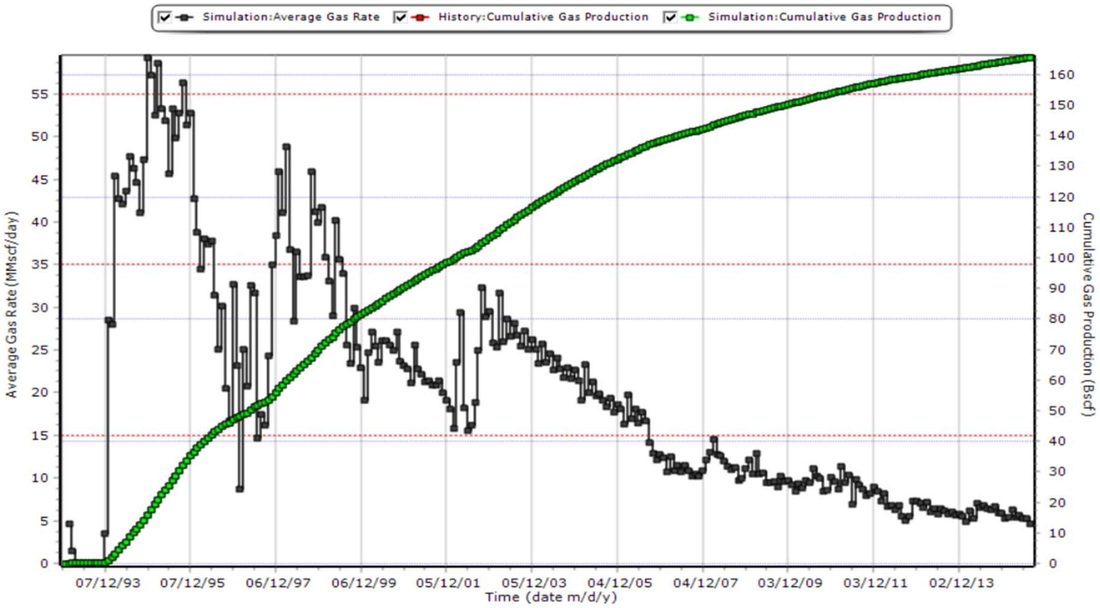
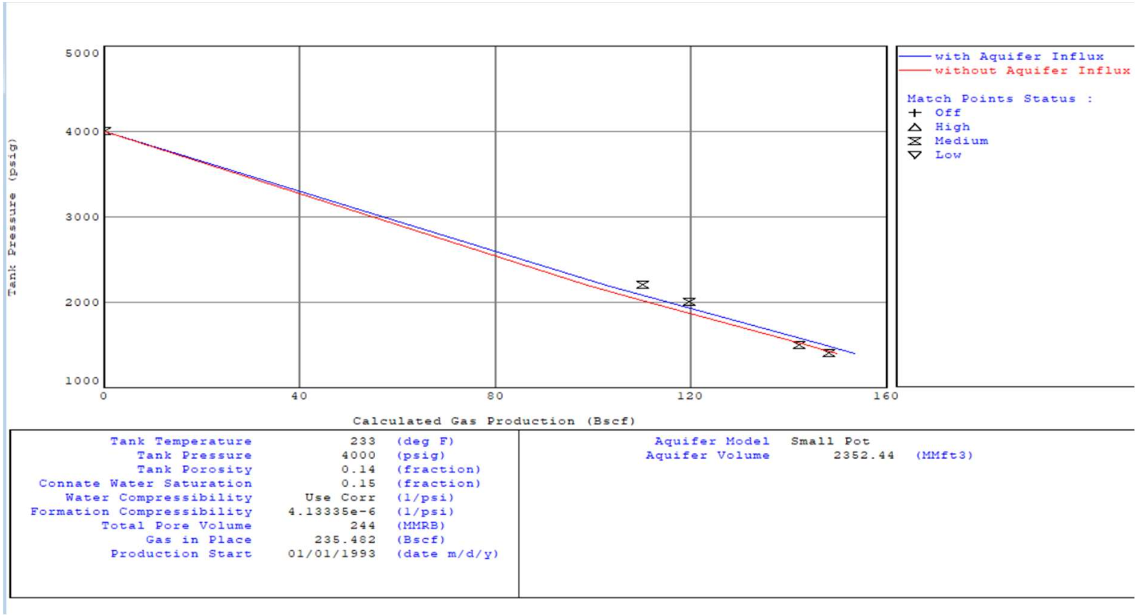


Figure 4-6: History Matching Results

Figure 4-7 shows matching of Reservoir P/z of model and actual reservoir pressure. This confirms Original Oil in Place of the reservoir and remaining reserves.



Tank Temperature	233	(deg F)
Tank Pressure	4000	(psig)
Tank Porosity	0.14	(fraction)
Connate Water Saturation	0.15	(fraction)
Water Compressibility	Use Corr	(1/psi)
Formation Compressibility	4.13335e-6	(1/psi)
Total Pore Volume	244	(MMRB)
Gas in Place	235.482	(Bscf)
Production Start	01/01/1993	(date m/d/y)

Aquifer Model	Small Pot	
Aquifer Volume	2352.44	(MMft3)

Figure 4-7: Analytical Modelling Results

Plot in figure 4-7 shows Injection and Production Cycles. As discussed in the methodology, depleted reservoir is considered in southern part of Pakistan near Sea Port. Total Capacity of this field is 48 BCF Gas. During the injection cycle 40 BCF of gas is stored and this gas is produced during the production cycle. There is declining trend of Injection and production rate because increase in the Reservoir Pressure. To counter this declining trend compressors are utilized which are already available at the facility.

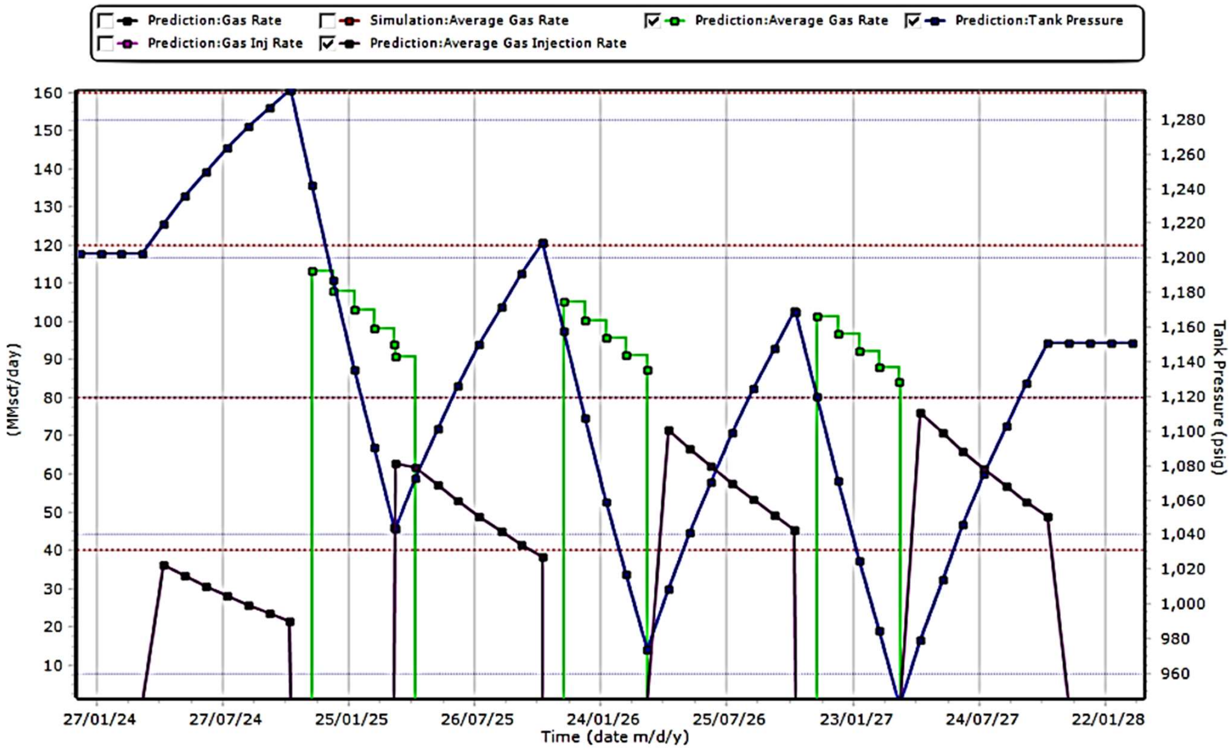


Figure 4-8 Injection and Withdrawal cycle

Gas injected is LNG as there is no other source of imported Gas available in the country. If TAPI Project and IP Gas Pipeline Project (Iran Pakistan Gas Pipeline) is completed, then Government will have more opportunity to utilize storage and stabilize consumers from fluctuation of international Gas Prices.

4.8 Optimization of Gas Procurement and Breakeven Cost Calculation

Python code is generated which incorporated all the constraints. Maximum capacity of injection is 40 BCF during injection cycle and during production cycle this much gas will be produced. 7 months of injection cycle is considered (April to Oct) and 5 months (Nov to Mar) of Production Cycle is considered.

Gas Price forecast along with cost of facility and LNG transportation to be provided to the algorithm and algorithm will make decision when to buy how much gas. As a thumb rule one LNG cargo can carry about 4 BCF of Gas. Based on price, algorithm will optimize injection quantity and procurement of cargos. Objective is to minimize overall cost of injection. Algorithm will then calculate breakeven cost by considering constant flow rate (250 MMSCFD) for next 5 months. This price will help to estimate price of Gas coming from Storage and Government can utilize this to save procurement of expensive seasonal gas.

4.8.1 Optimal Procurement Plan

The optimization process resulted in an optimal procurement plan that outlines the recommended quantities of gas to be procured during each of the seven months within the specified timeframe. The objective of the optimization was to minimize the total cost of gas procurement while considering variable gas prices and storage limitations. The optimal procurement plan is as follows

1. **Month 1** No gas procurement (0.00 BCF)
2. **Month 2** Procured 8.00 BCF
3. **Month 3** Procured 8.00 BCF
4. **Month 4** Procured 8.00 BCF
5. **Month 5** Procured 8.00 BCF
6. **Month 6** No gas procurement (0.00 BCF)
7. **Month 7** Procured 8.00 BCF

Total Procured Gas 40.00 BCF

Total Cost of Procurement (In Millions) $291.92

The procurement plan highlights the allocation of gas procurement quantities over the specified months, adhering to constraints while minimizing costs.

4.8.2 Breakeven Cost Estimation

The estimation of the breakeven cost of produced gas is a pivotal metric for understanding the point at which the investment in gas production becomes balanced with the procurement cost. Based on the provided information, the breakeven cost was calculated using the following steps

1. Calculate **X** Total Injection Cost / 152 = $291.92 / 152 = 1.9205
2. Compute **Y** X * 1000 / 250 = 7.682 $/MMBTU

Hence, the estimated **Breakeven Cost** 7.682 $/MMBTU

The breakeven cost signifies the gas cost at which the overall injection cost aligns with the cost of producing the stored gas. This value provides valuable insights into the economic feasibility of gas production at varying costs.

Following assumptions are made for this case study:

1. In this thesis, we assume a limited scope concerning the identification of a suitable Pilot field for Underground Gas Storage (USG) purposes without a significant capital expenditure (CAPEX) requirement. The focus will primarily be on the selection and evaluation of such a candidate field within the constraints of minimal CAPEX involvement.
2. The integrity considerations of wells and the reservoir within the selected candidate field for USG are not within the scope of this study. We assume that the chosen field possesses the necessary integrity and infrastructure for gas storage, and we do not delve into the detailed examination of these aspects.
3. High-end compression considerations for gas injection will not be explored in this thesis. We assume that the gas injection process into the selected field will occur without requiring advanced compression techniques, and we do not include an in-depth analysis of compression methods as part of this study.

Chapter 5. CONCLUSIONS AND FUTURE RESEARCH

This research is based on the energy requirement of Pakistan and how to optimize available resources and bring in new resources to bridge gap between demand and supply. There have been Trillion cubic feet of natural gas stored around the world and its very common but unfortunately there is no underground storage facility established in Pakistan.

5.1 Importance of UGS in Pakistan's Energy Security

Following are the importance of UGS:

1. UGS facility will serve as buffer against supply disruptions caused by geopolitical conflicts, natural disasters, or unexpected production fluctuations. These reserves ensure a consistent and reliable energy supply, enhancing a nation's energy security and reducing vulnerability to external shocks.
2. Natural gas demand often varies seasonally, with higher consumption during colder months. Underground storage enables the accumulation of surplus gas during periods of low demand and its release when demand peaks, ensuring a stable and continuous energy supply.
3. This UGS facility offer flexibility in managing fluctuations in energy demand and supply, contributing to the stability and reliability of energy grids. This is particularly valuable as more renewable energy sources are integrated, which can be intermittent in nature.
4. This UGS will make it possible to purchase of gas during periods of low demand or lower market prices and its subsequent release when prices rise. This practice will helps to stabilize gas prices and mitigate the impacts of market volatility.
5. This UGS facility will enable efficient use of surplus gas that may otherwise be wasted during periods of low demand. This resource optimization supports sustainability by reducing wastage and minimizing environmental impacts.
6. This UGS will serve as a crucial resource during emergencies, such as natural disasters or disruptions in supply. These reserves can be tapped into to meet essential energy needs during critical times.

7. As the global energy landscape shifts towards cleaner alternatives, UGS will facilitate the integration of renewable energy sources. Stored gas can be used for backup power generation during lulls in renewable energy production, ensuring continuous electricity supply.
8. Utilizing existing reservoirs, such as depleted oil and gas fields, for storage minimizes the need for additional infrastructure development, optimizing resource use and reducing environmental impact.
9. UGS will enhance competition by enabling market participants to manage supply and demand more effectively. This can lead to increased efficiency, innovation, and competitive pricing.
10. UGS will enable countries to participate more actively in international energy markets. They can buy gas when prices are low and store it for consumption or resale when prices are favorable, contributing to energy market dynamics.

5.2 Discussion on Research Question and Implications

The ensuing section presents a comprehensive discussion on the research question while delving into the realms of UGS optimization. This multifaceted exploration is underpinned by the 4A methodology Availability, Applicability, Acceptability, and Affordability. Within this discussion, we delve into the insights drawn from our investigation, elucidate the wider implications of the findings, and contextualize the outcomes within the broader energy security landscape.

5.2.1 Availability and UGS

Our scrutiny of energy availability underscores the intricacies of Pakistan's energy supply ecosystem, magnifying the significance of adopting UGS facilities. The country's reliance on energy imports accentuates vulnerability, underpinning the pressing need to diversify energy sources. The synergy between energy availability and the implementation of UGS takes center stage, offering a strategic mechanism to bolster domestic energy reserves and mitigate supply volatility.

5.2.2 Applicability and Optimization

The exploration of energy applicability, intertwined with optimization strategies, unveils avenues for harmonizing energy supply with dynamic demands while adhering to sustainable tenets. By synergizing renewable energy integration and the optimization of UGS, a cohesive framework emerges, steering energy solutions towards adaptability. The potency of this framework extends beyond the borders of Pakistan, resonating with global energy transition imperatives.

5.2.3 Acceptability

Amidst the discourse on energy acceptability, the interface between environmental stewardship and energy security shines through. The implications transcend conventional energy metrics, ushering in a holistic perspective that converges climate goals with energy imperatives. The discussion underscores the importance of embracing environmentally sound energy alternatives, fostering a harmonious equilibrium between energy security and ecological integrity.

5.2.4 Affordability

The investigation into energy affordability bridges the chasm between energy access and economic feasibility. The intricate interplay between affordability and energy aspirations is unpacked, casting a spotlight on strategies that prioritize equitable energy distribution while mitigating economic constraints. The equilibrium underscored here resonates in the context of UGS optimization, where economic considerations are intertwined with energy security imperatives.

As the implications of our research cascade the amalgamation of advanced reservoir modeling, wellbore optimization, linear programming, and UGS coalesces into a dynamic framework. This framework stands as a testament to adaptable energy management strategies, resonating across diverse energy landscapes and culminating in optimization paradigms.

In summation, this thesis embarks on the journey of optimizing gas management through underground storage facilities, emerging as a cornerstone pursuit in the contemporary energy panorama. Guided by the 4A methodology, our findings navigate the intricate tapestry of energy security. The implications, traversing beyond national contours, enrich the discourse for policymakers, researchers, and energy practitioners, as we collectively endeavor to cement the foundations of sustainable energy futures.

5.3 Recommendations

Following are the recommendations of this research:

1. Governments should formulate an UGS Policy to govern the development and operation of UGS facilities, ensuring effective energy security and gas supply management.
2. Implement preventive measures to avoid the abandonment of depleted oil and gas fields suitable for UGS, preserving these valuable resources for future energy needs.
3. Explore the possibility of privatizing gas distribution companies facing significant financial losses to promote operational efficiency and sustainability within the gas distribution sector.
4. Strategically build gas reserves to serve as buffers during supply disruptions, emergencies, or peak demand periods, ultimately enhancing overall energy security and stability.
5. Explore gas market and complete committed gas pipeline project with Iran and Turkmenistan (TAP). This would help to diversify Pakistan's gas imports and reduce its reliance on imported LNG. It would also help to ensure a stable supply of gas for power generation and other industrial uses.
6. Develop an optimization model for power generation and consumption. This would help to maximize the efficiency of Pakistan's power system and reduce the cost of electricity for consumers. The model would take into account factors such as the availability of different fuels, the cost of generating electricity, and the demand for electricity.
7. Increase % of indigenous coal in overall energy mix. This would help to reduce Pakistan's reliance on imported oil and gas. Thar coal is a low-cost, abundant resource that can be used to generate electricity and produce syngas for fertilizer production.
8. Invest in aging pipeline network and complete North South Pipeline Project. This would help to improve the efficiency of Pakistan's gas transportation system and reduce gas losses. The North South Pipeline Project would transport gas from the southern Sindh province to the northern Khyber Pakhtunkhwa province.

5.4 Research Limitations

While this study endeavors to provide a comprehensive exploration of optimizing gas management through UGS facilities in Pakistan, it is important to acknowledge certain limitations that may have impacted the scope and outcomes of the research:

1. The study heavily relies on the availability and accuracy of data from various sources, including energy yearbooks and reservoir data. Variations in data quality, completeness, and consistency could potentially introduce uncertainties in the modeling and analysis conducted.
2. The models used for reservoir simulation, wellbore optimization, and linear programming are based on simplifying assumptions. These assumptions may not capture all the complexities of real-world reservoir behavior, well interactions, and market dynamics, potentially affecting the accuracy of the optimization outcomes.
3. The level of detail and resolution of data used for analysis, particularly in reservoir modeling, may influence the accuracy of the results. Limited spatial and temporal granularity might restrict the precision of predictions related to gas storage dynamics.
4. While the findings of this study offer insights into optimizing gas storage in Pakistan, the applicability of the results to other regions or contexts may be subject to variations in energy market structures, geological characteristics, and regulatory frameworks.
5. The 4A methodology employed for energy security assessment involves subjective weighting and normalization of indicators. The weighting scheme and transformation process may influence the overall energy security index and could be perceived differently by stakeholders.
6. Due to the complex nature of the reservoir and optimization models used, a comprehensive validation process may have limitations. The accuracy of the models relies on the accuracy of input parameters and assumptions made during validation.
7. Economic parameters, such as gas prices and cost estimates, are inherently uncertain and subject to market fluctuations. These uncertainties can impact the economic evaluations and cost-benefit analyses conducted in the optimization process.

8. The optimization strategies considered in this study do not account for potential external factors that may impact gas storage operations, such as geopolitical events, regulatory changes, or unforeseen technological developments.
9. The research predominantly focuses on quantitative analyses and modeling techniques. Qualitative insights from stakeholders, policymakers, and experts could offer a more comprehensive understanding of the challenges and opportunities associated with UGS.
10. The research does not extensively explore future scenarios, such as changes in energy demand patterns, advancements in technology, or policy shifts. Incorporating such scenarios could further enrich the understanding of long-term energy security strategies.

It is crucial to recognize these limitations as they contribute to the holistic perspective of your research. By acknowledging these constraints, you demonstrate the conscientious approach taken in your study and set the stage for future research endeavors aimed at addressing these limitations and expanding the frontiers of knowledge in this domain.

5.5 Future Directions

Certainly, here is a more detailed exploration of potential areas for future research based on the themes and topics explored in your thesis on optimizing gas management through UGS facilities in Pakistan

1. Delve into advanced reservoir characterization techniques, including seismic imaging, well log analysis, and geostatistical modeling, to enhance the accuracy of reservoir models. Investigate the incorporation of geological heterogeneity, reservoir rock properties, and fluid behavior to create more realistic simulations that optimize gas storage operations.
2. Conduct in-depth research on the development of dynamic optimization models that consider various factors such as market demand, gas prices, reservoir characteristics, and operational constraints. Explore advanced optimization algorithms, including genetic algorithms and artificial intelligence, to determine optimal injection and withdrawal schedules for maximizing storage capacity and economic benefits.

3. Extend your research by incorporating thermo-hydromechanical (THM) modeling to capture the complex interactions between temperature, fluid flow, and mechanical behavior within the reservoir. Investigate how THM modeling can provide insights into subsurface pressure management, thermal expansion effects, and potential risks related to reservoir deformation.
4. Deepen your investigation into wellbore design by considering the influence of wellbore geometry, completion techniques, and materials on gas injection and withdrawal efficiency. Analyze the potential of utilizing advanced materials and wellbore technologies, such as intelligent completion systems and inflow control devices, to optimize well performance and minimize production risks.
5. Explore the integration of UGS facilities with carbon capture and storage technologies. Investigate how CO2 capture from industrial processes or power plants can be injected into depleted reservoirs, not only reducing emissions but also enhancing gas storage capacity through enhanced oil recovery mechanisms.
6. Address the energy-water nexus by studying the interaction between gas storage operations and water resources. Investigate how reservoir water influx or produced water management can impact gas storage efficiency and assess strategies to mitigate potential challenges related to water accumulation.
7. Undertake comprehensive research to assess the socio-economic impact of UGS facilities on local communities, job creation, and regional development. Incorporate stakeholder engagement, economic modeling, and qualitative analysis to provide insights into the broader implications of such projects.
8. Focus on the development of real-time monitoring and control systems that use advanced sensors, data analytics, and predictive algorithms to optimize gas storage operations. Investigate how these systems can enhance operational efficiency, early detection of anomalies, and adaptive control strategies.
9. Extend your research to explore the feasibility of using UGS facilities for hydrogen storage. Investigate the technical and economic viability of converting excess

renewable energy into hydrogen and storing it in depleted reservoirs for later utilization in various sectors, including power generation and transportation.

10. Broaden your research scope to analyze the potential for international collaboration in gas storage projects. Investigate how Pakistan's strategic location can facilitate cross-border energy cooperation, fostering diplomatic ties and energy trading with neighboring countries, including India, China, and Iran.

These detailed future research areas offer opportunities to expand upon the themes of your thesis, contributing to a deeper understanding of optimizing UGS operations in Pakistan and their implications for energy security, sustainability, and regional cooperation.

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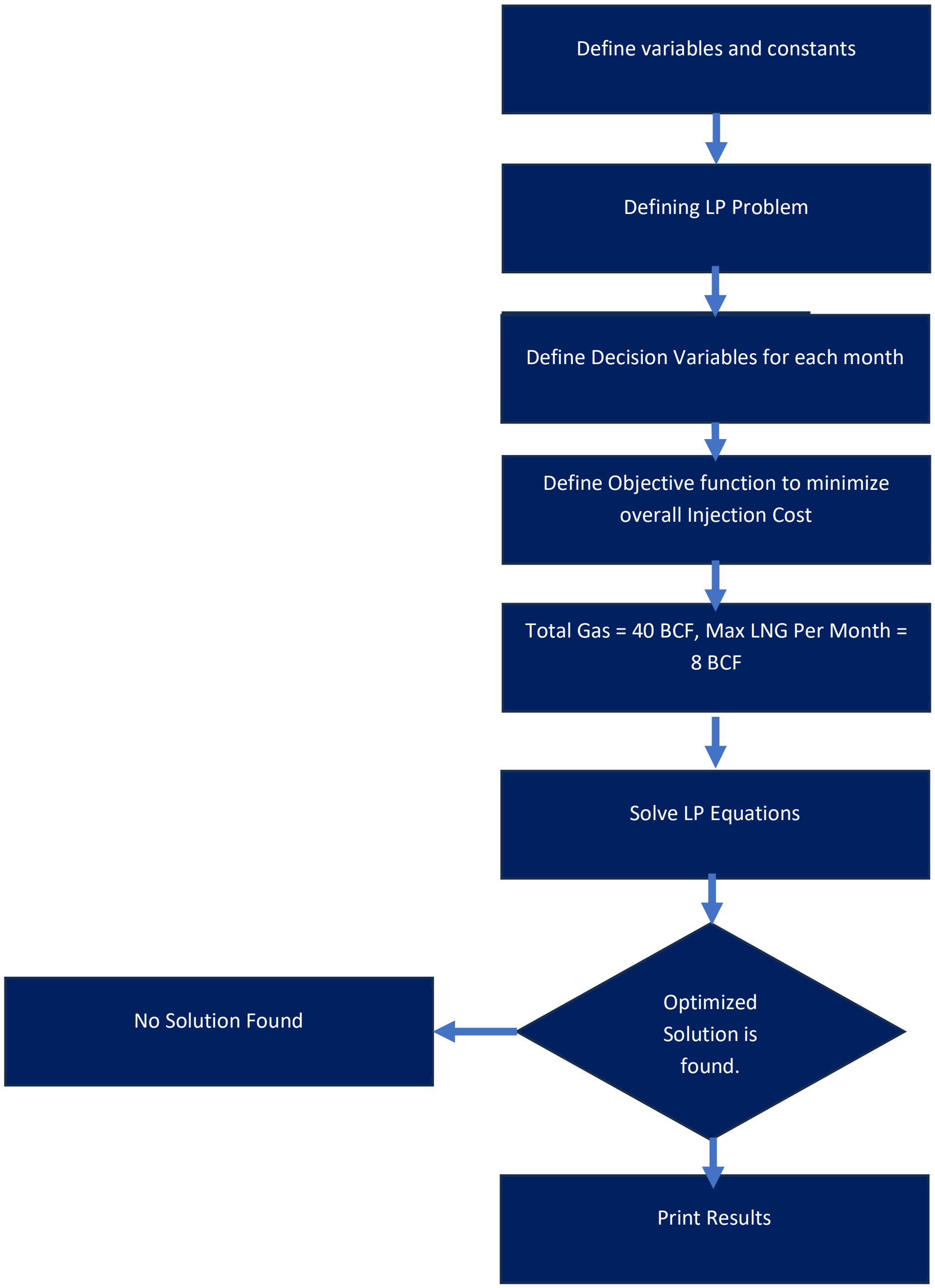
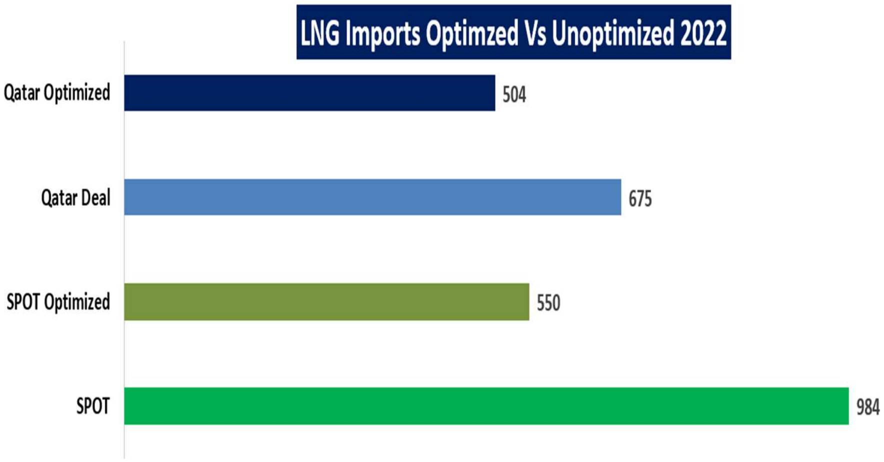
APPENDICES

APPENDIX A

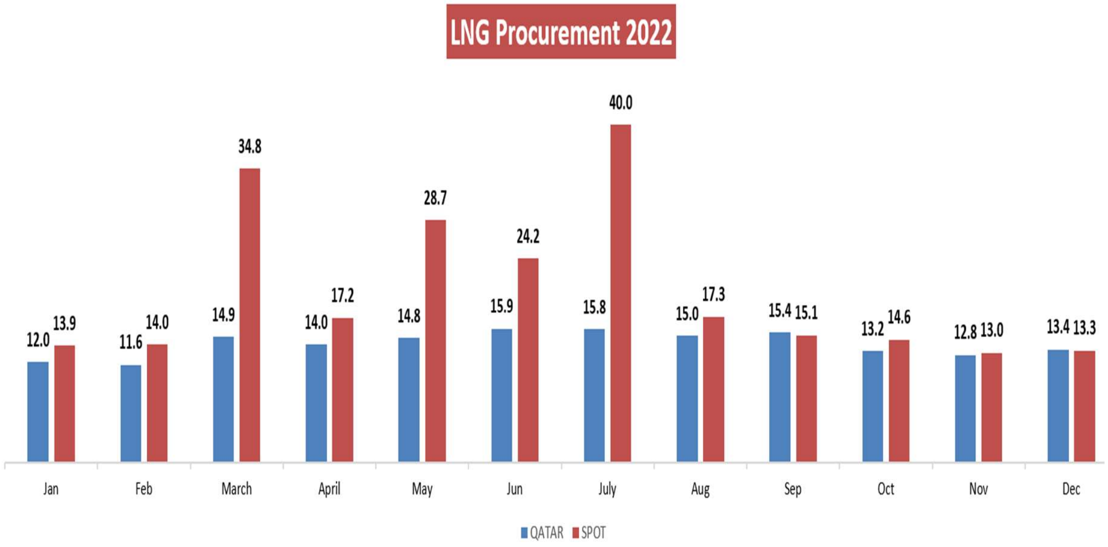
```
from pulp import *
# Define the number of months
num_months = 12
# Define the gas prices for each month (in $/MMBTU)
gas_prices = [13.8, 13.9, 34.8, 17.19, 28.7, 28.71, 24.2, 40, 17.2, 15.1, 14.5, 13.0, 13.3]
# Create the Linear Programming problem
prob = LpProblem("GasProcurement", LpMinimize)
# Define the decision variables for gas procurement
procurement_vars = LpVariable.dicts("procurement", range(num_months), lowBound=0,
upBound=8, cat="Integer")
# Define the objective function to minimize the total cost of gas procurement
prob += lpSum(gas_prices[i] * procurement_vars[i] for i in range(num_months))
# Define the constraint for total gas procurement
prob += lpSum(procurement_vars[i] for i in range(num_months)) == 40
# Solve the Linear Programming problem
prob.solve()
# Print the optimized results
if LpStatus[prob.status] == "Optimal":
    print("Optimal Procurement Plan:")
    for i in range(num_months):
        print(f"Month {i+1}: Procured {procurement_vars[i].varValue:.2f} BCF")
          print(f"\nTotal Procured Gas: {sum(procurement_vars[i].varValue for i in
range(num_months)):.2f} BCF")
    print(f"Total Cost of Procurement: ${value(prob.objective):.2f}")
    # Constants for breakeven cost estimation
    total_injection_cost = value(prob.objective)
    X = total_injection_cost / 152
    Y = (X * 1000) / 250

    # Print the breakeven cost
    print(f"Breakeven Cost of Produced Gas: ${Y:.2f}/MMBTU")
else:
    print("No optimal solution found.")
```

Flow Chart of Model





LNG Imports Optimzed Vs Unoptimized 2022



LNG Procurement 2022

APPENDIX B

International Pipeline Projects

1. Turkmenistan-Afghanistan-Pakistan-India (TAPI) Pipeline

The TAPI pipeline is a landmark project that aims to connect Turkmenistan's vast Galkynysh gas field to energy-hungry markets in Afghanistan, Pakistan, and India. Pakistan's participation in this project demonstrates its commitment to regional cooperation and energy diversification. The pipeline is anticipated to address Pakistan's growing energy demand, stimulate economic growth, and enhance energy security by providing a steady supply of natural gas from a reliable source.

2. Pakistan-Iran Gas Pipeline (Peace Pipeline)

The Pakistan-Iran Gas Pipeline, also known as the Peace Pipeline, was designed to alleviate Pakistan's energy crisis by importing natural gas from Iran. This project held immense strategic significance, potentially enhancing Pakistan's energy security and economic stability. However, geopolitical complexities, international sanctions, and financing challenges have hindered its progress. Despite the hurdles, the pipeline remains a significant example of Pakistan's efforts to secure energy resources through regional partnerships.

i. China-Pakistan Economic Corridor (CPEC) Gas Pipeline

As a key component of the broader CPEC initiative, the China-Pakistan Gas Pipeline is set to connect Gwadar Port in Pakistan to Kashgar in China's Xinjiang region. This ambitious project underscores Pakistan's role as a crucial energy corridor, facilitating China's access to energy resources and markets. The pipeline not only enhances bilateral ties between Pakistan and China but also elevates Pakistan's geostrategic importance as a conduit for energy trade and economic connectivity.

ii. Tajikistan-Afghanistan-Pakistan-India (TAPI) Electricity and Gas Grid Interconnection

Beyond the conventional gas pipeline, the TAPI project envisions an integrated energy corridor that interconnects electricity and gas networks. Pakistan's involvement in this initiative showcases its commitment to sustainable and comprehensive energy solutions. The interconnection could potentially lead to a more resilient energy grid, allowing the exchange of surplus electricity and gas among the participating countries, thereby fostering regional stability and energy cooperation.

iii. Iran-Pakistan-India (IPI) Gas Pipeline (Prospective)

The IPI gas pipeline project, although still in the prospective stage, signifies Pakistan's efforts to explore diverse energy options. The potential pipeline would transport Iranian gas to Pakistan and India, further diversifying Pakistan's energy sources and reducing its dependence on a single supplier. If realized, this project could contribute to enhanced energy security and stability in the region.

iv. Pipeline Connectivity with Russia (Prospective)

Pakistan's interest in exploring gas pipeline connectivity with Russia reflects its commitment to exploring new avenues for energy procurement. A potential pipeline from Russia could provide an additional source of natural gas, contributing to Pakistan's energy security and offering greater flexibility in managing its energy mix.

These international gas pipeline projects showcase Pakistan's strategic approach to energy diplomacy and its eagerness to foster regional cooperation. While some projects have faced challenges, they underscore Pakistan's determination to secure stable and diversified energy sources, stimulate economic development, and strengthen diplomatic ties with neighbouring countries and beyond.

Strategic Location of Pakistan

Pakistan's strategic location holds immense importance in the global gas market due to a multitude of factors that make it a pivotal player in energy dynamics

1. **Energy Corridor and Transit Hub** Pakistan's geographical location places it at the crossroads of energy-rich regions, including the Middle East, Central Asia, and South Asia. This positioning allows Pakistan to serve as a crucial energy corridor and transit hub, facilitating the transportation of natural gas and other energy resources between these regions. Its role as a transit country enables the seamless movement of energy supplies, promoting regional energy integration and cooperation.

2. **Connectivity to Energy-Rich Regions** Pakistan's proximity to major natural gas producers such as Iran and Turkmenistan enhance its attractiveness as a destination for energy transit and trade. Its accessibility to these energy-rich regions opens avenues for diversifying energy sources and routes, thereby reducing dependency on a single supply route and bolstering energy security.
3. **Global Energy Routes and LNG Trade** The Arabian Sea coastline offers Pakistan access to key international shipping routes, making it an ideal location for the import and export of energy resources. This strategic advantage positions Pakistan as a potential player in the global liquefied natural gas (LNG) trade. The deep-sea port at Gwadar further enhances this potential, allowing for efficient handling and transportation of LNG shipments.
4. **China-Pakistan Economic Corridor (CPEC) Impact** Pakistan's involvement in the China-Pakistan Economic Corridor (CPEC) elevates its strategic importance. The corridor includes energy infrastructure projects like the Gwadar Port and cross-border pipelines, enabling energy imports and exports between China and the Middle East. This strengthens Pakistan's role as a conduit for China's energy needs and reinforces regional connectivity.
5. **Regional Stability and Energy Security** Pakistan's stable political environment and responsible foreign policy contribute to its status as a reliable energy transit route. Its stability ensures the smooth flow of energy resources, promoting regional energy security. By providing a secure transit corridor, Pakistan contributes to the stability of energy supply chains and economic growth in energy-importing countries.
6. **Large Consumer Market** Pakistan's substantial population and expanding economy make it an attractive consumer market for energy exporters. Its strategic location offers energy producers access to a burgeoning consumer base, potentially fostering mutually beneficial trade agreements and partnerships.
7. **Energy Diplomacy and Collaboration** Pakistan's strategic position allows it to engage in energy diplomacy and collaboration with energy-producing and consuming nations. By facilitating energy trade agreements and partnerships, Pakistan can strengthen

diplomatic ties, build economic cooperation, and attract foreign investments in its energy sector.

8. **Infrastructure Development and Revenue Generation** Acting as a transit country for energy resources generates transit fees and revenue, which can be invested in infrastructure development and energy projects. These investments contribute to economic growth and support the modernization of energy infrastructure.
9. **Geopolitical Influence and Energy Policies** Pakistan's strategic location grants it geopolitical influence in energy affairs. By engaging in international energy initiatives and collaborations, Pakistan can shape energy policies, contribute to regional stability, and facilitate dialogue on sustainable energy development.

In conclusion, Pakistan's strategic positioning in the gas market is a key determinant of its role as a regional and global energy player. Leveraging its geographic advantage allows Pakistan to enhance its energy security, foster economic growth, strengthen diplomatic relations, and contribute to a more integrated and sustainable energy landscape.

LNG Deals of Pakistan

Pakistan has entered into several liquefied natural gas (LNG) deals to address its energy needs, diversify its energy sources, and ensure a stable supply of natural gas. These deals have played a significant role in meeting the country's energy demands and enhancing its energy security. Here are some key details of Pakistan's major LNG deals

1. **Qatar LNG Deal**
    - Supplier Qatar Gas
    - Term Long-term agreement signed in 2016
    - Quantity Approximately 3.75 million tons of LNG annually
    - Price A fixed formula linked to the crude oil price index
    - Purpose To alleviate energy shortages and stabilize natural gas supply
2. **Gunvor LNG Deal**
    - Supplier Gunvor Group

- Term Five-year agreement signed in 2015
- Quantity Around 2.25 million tons of LNG per year
- Price A combination of a fixed component and a floating component tied to Brent crude prices
- Purpose To augment LNG supplies and cater to increasing energy demand

3. **Eni LNG Deal**
    - Supplier Eni (Italy's state-owned energy company)
    - Term Long-term agreement signed in 2015
    - Quantity Approximately 180,000 tons of LNG per year
    - Price Linked to Brent crude oil prices
    - Purpose To diversify LNG sources and enhance energy security
4. **Gulf Trading LNG Deal**
    - Supplier Gulf Trading (Swiss energy company)
    - Term Short-term agreement signed in 2017
    - Quantity Varies based on market demand
    - Price Linked to a floating index, including Henry Hub and Brent crude prices
    - Purpose To meet short-term LNG requirements and address seasonal fluctuations
5. **LNG Spot Market Purchases**
    - Supplier Various global LNG suppliers
    - Term Short-term and spot purchases
    - Quantity Flexible and based on market conditions
    - Price Linked to prevailing LNG market rates

- Purpose To quickly address energy shortfalls and take advantage of favorable market conditions.

These LNG deals have been instrumental in addressing Pakistan's energy challenges by providing a reliable and diverse source of natural gas. They have played a vital role in improving energy availability, reducing energy deficits, and stabilizing gas supplies for industrial, residential, and power generation sectors. The agreements reflect Pakistan's commitment to securing energy resources through international collaborations and promoting energy security in the face of growing energy demand.