Assessment of Power Generation Through Pressure Reduction in High Pressure of Sui Northern Gas Pipelines (SNGPL) Pakistan

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Abstract- The unutilized natural gas resources of 1,559 billion cubic feet per year within Pakistan occur because Sales Metering Stations (SMSs) handle pressure reduction inefficiently. This paper evaluates power generation possibilities by implementing Turbo Expanders instead of throttling valves in SNGPL's high-pressure transmission lines that operate between 600 and 1200 psig. We evaluated energy recovery potential at three Sales Metering Stations Naughazi, Rawat and Ranial which service the Islamabad and Rawalpindi areas using Aspen HYSYS® simulations and theoretical calculations. The monthly power generation potential based on study results stands at 361.62 MW per month and 23,149 MW per month could be achieved through the 433 SMSs in SNGPL's network. TE devices promote power efficiency in operations by decreasing utility waste while promoting safeguarding environmental resources. The research presents a scalable power solution for Pakistan's energy crisis that would generate estimated monthly economic value worth $168 million at the $0.10/kWh rate while further costing assessment must be completed.

Keywords- Pressure into Power, Sales Metering Station, Turbo Expanders, Natural Gas.

List of Abbreviations-

SNGPL: Sui Northern Gas Pipelines Limited
SSGCL: Sui Southern Gas Company Limited
SMS: Sales Metering Station
TE: Turbo Expander
PIP: Pressure into Power
PCV: Pressure Control Valve
MW: Megawatt
hp: Horsepower
MMCFD: Million Cubic Feet per Day
MCF: Thousand Cubic Feet
MMBTU: Million British Thermal Units

I. INTRODUCTION

Natural gas serves as one of the essential fuels for global energy systems because it is both domestically produced and clean-burning as a fossil fuel source. High-pressure pipelines transport natural gas along 600–1200 psi pressure ranges to fulfill essential electricity production and industrial processes as well as domestic energy requirements. The energy potential of natural gas encompasses three forms of exergy: chemical, thermal, and pressure exergy. Widespread use of chemical energy occurs through power plant and industrial combustion but high-pressure gas streams carrying pressure exergy stay unused as they move through distribution systems. Maximizing pressure exergy utilization presents a big missed opportunity in energy-scarce areas because efficient resource management is essential to support economic advancement together with environmental sustainability goals.

The energy policy of Pakistan depends heavily on natural gas which provides economic stability and secure energy access to the country. The country obtains its main supply of energy from natural gas which exists in 24 trillion cubic feet recoverable reserves with daily output at 4 billion cubic feet [1-2]. Numerous energy losses occur from pressure reduction inefficiencies at Sales Metering Stations (SMSs). The current distribution method uses throttling valves which lead to pressure reduction through the isenthalpic process while converting pressure exergy into heat. Research has determined that gas pressure reduction operations at the Sales Metering Stations of Sui Northern Gas Pipelines Limited (SNGPL) in Pakistan generates a monthly energy deficit of 400–500 MW which could otherwise be recovered through analysis of flow rates and pressure losses [2-3]. The energy-wasting technique leads to operational complications which can form hydrates due to temperature reductions requiring supplemental prevention systems.

Turbo-expansion (TE) is a promise solution to address these inefficiencies. The advantage of TEs is that they convert pressure exergy into mechanical work, a type of mechanical work that can power an electricity generator or other mechanical systems. In addition to cold gas streams with possible industrial cooling applications, the expansion process also produces cold gas streams. TE deployments throughout the globe have successfully recovered pipeline energy for hydrogen production, hybrid power system and cogeneration plant applications [3-4]. Pressure to Power (P2P) integration at rural SMS's can meet both energy recovery and allow optimization of the existing natural gas infrastructure in Pakistan.

This study appraises the potential of power generation from TEs at three main SMSs of the SNGPL network, namely Naughazi, Rawat and Ranial. We use Aspen HYSYS® simulations tools to analyze energy recovery opportunities at these sites and generalize the results to the observation of SNGPL's 433 SMSs. Estimates of the single three SMS have generated 361.62 MW per month or about 16,500 GWh of potential power. P2P system implementations will enhance energy efficiency, minimize losses in operations and facilitate sustainable power generation in Pakistan. It further justifies the immediate need to exploit pressure exergy for better utilization of natural gas as a distributed medium in the nation's network.

Problem Statement

The inefficient pressure reduction at Sales Metering Stations (SMSs) within Pakistan's Sui Northern Gas Pipelines Limited (SNGPL) network results in significant energy waste. This study aims to assess the potential for power generation by replacing throttling valves with turbo expanders at key SMS locations, thereby recovering wasted pressure exergy and contributing to Pakistan's energy security.

II. LITERATURE REVIEW

Clean domestic fossil fuels generate natural gas as an energy source that is gaining increasing popularity. The transportation system consisting of transmission and distribution pipes delivers most of the natural gas that reaches the end-users. Pipelines used for transmission operate with pressure ranges between 1000 and 1200 PSI. There are three types of exergy (available energy) in natural gas flow through high pressure pipelines: pressure, thermal, and chemical exergy. Processing natural gas through combustion activates chemical energy conversion into alternative usable forms. The production of electricity together with heating houses remains by far the most prevalent application of natural gas energy in present-day society [5-6].

A serious power crisis exists in Pakistan today. The country depends heavily on natural gas as an energy source though it holds large untapped prospects for power generation applications. This paper evaluates the possibility of turbo expanders at Sales Metering Stations (SMSs) operated by SNGPL in Pakistan through Pressure-into-Power (PIP) systems. This research analyzes Naughazi Rawat and Ranial SMSs through Aspen HYSYS® simulation tools to determine their capacity and energy efficiency in power generation. This research calculates the wasted energy amounts present in the selected locations and evaluates how turbo expander installations would benefit from this energy source recovery. The extensive 433 SMS (compressor stations) network in Pakistan makes this research significant because it reveals how PIP systems implementation could generate additional power and boost sustainability across the system. The nation confronts a major energy emergency because of its existing power shortage problem [1]. Natural gas together with oil acts as Pakistan's main energy resources in its fuel mix. Pakistan possesses significant natural gas resources equivalent to 24 trillion cubic feet and near-daily output reaches 4 billion cubic feet [1, 7]. Natural gas applications for power generation require immediate enhancement of existing methods.

The distribution of natural gas from its transmission systems under high pressures (600-1000 psig) extends to major urban areas where end users receive the gas [8-9]. The Oil and Gas Regulatory Authority Ordinance from 2002 requires pressure regulation at 300 psig or less through pressure reduction stations for use in homes and industries [3]. The conventional pressure reduction method with throttling valves causes a major waste of energy, through the isenthalpic expansion process throttling valves perform pressure reduction by efficiently lowering gas temperature (Howard, 2003). Compression of material through 1 MPa induces a temperature decrease between 4.5 to 5°C [2, 10].

Conventional throttling poses important hazards because rapid temperature drops may result in hydrate formation and heavier hydrocarbon condensation [4, 12]. Distribution lines face the potential for obstruction from these events. The requirement for preheating the gas before throttling increases when significant temperature drops occur [4, 13]. TEs provide an alternative method to throttling valves as described [1, 14]. TEs extract the pressure energy from natural gas streams to produce mechanical power for electricity production or to operate compressors or other devices [1, 15]. TEs generate distinctive amounts of cold gas output throughout their expansion sequence while offering potential uses in cooling systems [1, 16].

Transmission networks transporting natural gas require high-pressure operation within the range of

600–1200 psi. These pressures reduce their magnitude during end user distribution through isenthalpic expansion achieved with throttling valves. Natural gas transmission system pressure decrease results in pressure exergy dissipation that produces a major energy waste [1, 17]. The placement of turbo-expanders in place of conventional throttling methods reveals massive unwanted energy recovery possibilities in these systems [2, 18].

Research on pressure recovery approaches in natural gas systems has received worldwide attention. Through computer simulations of Iran's natural gas transmission network discovered substantial possibilities for recovering wasted energy [1, 19]. A feasibility study in Bangladesh determined pressure-reduction station energy potential while promoting turbo-expanders as widespread deployment solutions [2, 20]. Researchers have reported similar findings to U.S. and European studies which implement turbo-expanders to boost system sustainability alongside increased energy efficiency [5-6, 21].

Turbo-expanders serve as mechanical tools which transform natural gas pressure energy into mechanical power through their operation. The converted mechanical energy serves two purposes for power generation while also operating auxiliary equipment systems [6, 22]. During turbo-expansion the system generates cold gas that can serve two roles: it provides cooling capabilities for systems and enhances industrial process efficiency [5, 23]. A dependent assessment shows that turbo-expanders gain acceptance to retrieve 80% of pressure exergy under considering site-specific conditions along with operational variables [7, 24].

Turbo-expander possibilities across the SNGPL network by studying sales metering stations (SMSs) for substantial power recovery potential in Pakistan [1, 25]. The analysis demonstrated that implementing turbo-expanders at existing pressure-reduction stations could lead to major energy savings which help Pakistan achieve its sustainability targets for energy. Aspen HYSYS simulations demonstrated that adding turbo-expanders into Pakistan's natural gas network meets economic and technical criteria for power production [8, 26].

Energy recovery represents only one application among multiple uses of turbo-expanders. Natural gas pipelines show evidence of combined turbo-expander systems which achieve electricity generation together with hydrogen production [5, 22]. Researchers explored the combination of turbo-expanders with renewable energy technologies such as solar and wind to boost natural gas network sustainability and efficiency [9, 24].

The use of turbo-expander systems has been proven viable through case studies from Iran and Bangladesh and Pakistan. How turbo-expanders work effectively in Iran’s natural gas system to reduce energy waste and build more dependable networks [1, 27]. Pakistan-based examples of turbo-expanders to show how these technologies could handle the nation's energy emergency situation.

The design of PIP systems uses different configurations that depend on site characteristics alongside output specifications [1, 28]. The installation of TEs alongside pressure reduction valves functions as a standard practice which improves system robustness. The system generates electricity that could either enter local power facilities or become available for storage because of changing natural gas conditions [1, 29]. Seasonal fluctuations in natural gas pressure levels force PIP systems to function like renewable energy devices including solar power and wind power. The proposed power generation design features a turbo-expander operating in sequence with existing pressure reduction facilities at [4, 30]. Profitable TE expansion leads to substantial gas temperature reductions amounting to 15-20°C per MPa. A pre-heater protects against water condensation by keeping the gas temperature at the TE outlet above hydrocarbon and water dew point conditions [4, 31].

Researchers have analyzed multiple approaches for extracting pressure potential from natural gas transmission pipelines. HYSYS-based computer model to examine the electricity generation potential throughout Iran's entire natural gas transmission system. Bangladesh researchers carried out similar investigations for measuring power generation possibilities from pressure reduction stations [2, 32]. ULER recalled hybrid TE-fuel cell performance at pressure reduction stations with their study alongside Maddaloni and Rowe's exploration of TEs for hydrogen production there.

The natural-gas flow through a throttling valve can be considered as the flow through a non-adiabatic control volume with one inlet and one outlet as shown in Figure 1. For such an open system with heat transfer to the environment at temperature T0, the first and the second laws of thermodynamics can be applied as follows:

First Law of Thermodynamics:

$$W^{\cdot} = Q^{\cdot} + m^{\cdot}(h + 2_v^2 + g_z)_{in} - m^{\cdot}(h + 2_v^2 + g_z)_{out} \text{ ---} \quad (1)$$

where:

$W^{\cdot}$ *is the rate of work done by the system*
$Q^{\cdot}$ *is the rate of heat transfer to the system*
$m^{\cdot}$ *is the mass flow rate*
h *is the specific enthalpy*
v *is the velocity*
g *is the acceleration due to gravity*
z *is the elevation*

Second Law of Thermodynamics:

The second law of thermodynamics can be expressed in terms of exergy, which represents the maximum useful work that can be obtained from a system or process. The exergy balance for a control volume can be written as:

$E^{\cdot}x = E^{\cdot}x, in - E^{\cdot}x, out - E^{\cdot}x, dest$ --- (2)

where:

$E^{\cdot}x$ *is the rate of exergy transfer*

$E^{\cdot}x, in$ *the rate of exergy entering the control volume*

$E^{\cdot}x, out$*is the rate of exergy leaving the control volume*

$E^{\cdot}x, dest$ *is the rate of exergy destruction due to irreversibilities within the control volume*

The exergy destruction term accounts for losses due to factors such as friction, heat transfer, and pressure drops. In the case of a throttling valve, the primary source of exergy destruction is the irreversible pressure drop. By analyzing the exergy balance, it is possible to quantify the energy losses associated with the throttling process and identify potential opportunities for improvement.

For a steady-state, open system, the first law of thermodynamics can be written as:

$Q^{\cdot} - W^{\cdot} = m^{\cdot}[(h + 2_v^2 + g_z)_{out} - (h + 2_v^2 + g_z)_{in}]$ --- (3)

Neglecting potential and kinetic energy changes:

$Q^{\cdot} - W^{\cdot} = m^{\cdot}(h_{out} - h_{in})$ --- (4)

Rearranging the equation:

$W^{\cdot} = Q^{\cdot} - m^{\cdot}(h_{out} - h_{in})$ --- (5)

Introducing the Second Law of Thermodynamics:

The rate of entropy generation within the control volume is given by:

$S^{\cdot}gen = T_oQ^{\cdot} - m^{\cdot}(s_{out} - s_{in})$ --- (6)

Eliminating heat transfer (Q):

From the first law equation:

$Q^{\cdot} = W^{\cdot} + m^{\cdot}(h_{out} - h_{in})$ --- (7)

Substituting this value of Q˙ in the entropy generation equation:

$S^{\cdot}_{gen} = T_oW^{\cdot} + m^{\cdot}(h_{out} - h_{in}) - m^{\cdot}(s_{out} - s_{in})$ --- (8)

Rearranging to get the expression for work (W):

$W^{\cdot} = T_oS^{\cdot}_{gen} + m^{\cdot}(h_{in} - T_os_{in}) - m^{\cdot}(h_{out} - T_o s_{out})$-- (9)

Thus we have

$W^{\cdot} = m^{\cdot}(h - T_os)in - m^{\cdot}(h - T_os)_{out} - T_oS^{\cdot}_{gen}$ --- (10)

Maximum Work (W_{rev}):

Since entropy generation (S˙gen) is always greater than or equal to zero, the maximum work output occurs when S˙gen=0.

$W^{\cdot}rev = m^{\cdot}(h - T_os)_{in} - m^{\cdot}(h - T_os)_{out}$ -- (11)

Introducing Specific Flow Exergy:

The specific flow exergy (ex) is defined as:

and we have

$e_x = (h - h_o) - T_o(s - s_o)$ -- (12)

Maximum Work in terms of Specific Flow Exergy:

Using the definition of specific flow exergy, Equation 4 can be rewritten as:

and

$W^{\cdot}rev = m^{\cdot}(e_x)_{in} - m^{\cdot}(e_x)_{out}$ -- (13)

The actual work output (W˙) will always be less than the maximum work (W˙rev) due to irreversibility within the system. The exergetic efficiency (e) is defined as the ratio of the actual work output to the maximum possible work output:

Finally we have

$W^{\cdot} = eW^{\cdot}rev$ -- (14)

People well recognize the numerous advantages of turbo-expanders but their deployment creates multiple technical difficulties with operational implications. Expansions through turbo-expander systems present a dual threat because hydrate formations combined with heavier hydrocarbon condensation obstructs pipeline contents [5, 31]. Preheaters are implemented for maintaining gas temperatures above hydrocarbon and water dew points to support the safe use of turbo-expanders [9-10].

Natural gas pressure recovery systems must deal with the pressure and flow variations which stem from seasonal changes. Studies indicate that turbo-expanders should be incorporated either with energy storage solutions or TE-fuel cells hybrid systems to properly balance sudden changes in operating conditions [3]. Research into site-specific elements including flow rates and pressure levels along with current infrastructure enable optimized operation of turbo-expander systems [5, 11, 32].

III. METHODOLOGY

In this study, pressure to power (P2P) systems using turbo expanders at Sales Metering Stations (SMSs) in Sui Northern Gas Pipelines Limited (SNGPL)’s Pakistan network are investigated as a means of potential power generation. Three representative SMS sites (Naughazi, Rawat, and Ranial) are data collected with Aspen HYSYS® simulations to direct the future employment of energy recovery opportunities. Stages of the approach are divided into four key stages: data collection, simulation model development, extrapolation to monthly and network wide scales, and financial or operational analysis. Reliability of the findings is ensured by validation and uncertainty analyses.

We collected operational data from the Naughazi, Rawat and Ranial SMS sites of SNGPL network that manages the flow and pressure in the gas flow and pressure regulation of 433 in the SMS of the Pakistan. The dataset included:

- Measured natural gas volumes (in million standard cubic feet per day, MMSCFD) at each SMS: recorded hourly over a 12-month period to capture seasonal variations daily flow rates.

- Gas Composition: Estimated during each site, confirmed by C0, and methane (usually >85%) and other hydrocarbons (e.g., ethane, propane) for the thermal and exergy analyses.
- Inlet / Outlet Details: Inlet (600-1200 psig) and outlet pressures (typically 150-200 psig) measured using calibrated pressure gauges, and seasonal variations noted.
- Data of Temperature: Ambient and pipeline gas temperature with readings taken by thermocouples, for exergy loss and hydrate formation risk calculations.

The SNGPL field instruments directly measured data, and although there were minor estimations to fill some of the occasional gaps that is during maintenance downtimes, the azimuth and tracking rates were used from historical averages.

Aspen HYSYS® 7.1 was employed to model the P2P system, replacing conventional throttling valves with turbo-expanders. The simulation process involved:

- Input Parameters: Measured flow rates, inlet pressures, temperatures, and gas compositions were input to replicate SMS conditions.
- Turbo-Expander Integration: The throttling valve was substituted with a turbo-expander module, calculating mechanical energy output (in horsepower, hp) and power generation potential (in MW) based on pressure drop and flow exergy.
- Thermodynamic Analysis: Energy losses during throttling were quantified using the first and second laws of thermodynamics, with specific flow exergy calculated as:

$$\dot{E}_x = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad \text{-- (15)}$$

where

$\dot{m}$ is mass flow rate, h and s are specific enthalpy and entropy, and subscript 0 denotes reference conditions (25°C, 1 atm).

- Pre-Heater Module: A pre-heater was modeled to maintain gas temperatures above hydrocarbon and water dew points, preventing hydrate formation during expansion.
- Operational Scenarios: Multiple scenarios that is peak vs. off-peak demand were simulated to evaluate system efficiency.

Model Validation

Simulation results of energy recovery efficiencies and pressure drop values in Aspen HYSYS model were compared with results of operational data for similar natural gas networks from Iran and Bangladesh as reported in the literature [1-2]. Here as an example, we note that energy recovery rates were within 5 % of the values in Iran's turbo expander systems that range from 0.8 to 1.2 kWh of gas processed per kg. A sensitivity analysis also indicated robustness by assessing the power output variation of up to ±10% of the flow rate, pressure, and composition as inputs.

Uncertainty Analysis

Uncertainty in the simulation stemmed from measurement errors (±2% for flow rates, ±1% for pressures) and gas composition variability (±0.5% methane content). Monte Carlo simulations (1000 iterations) were conducted in Aspen HYSYS to quantify uncertainty, yielding a 95% confidence interval for daily power output at each SMS that is ±3.5 MW at Naughazi. Seasonal demand fluctuations were also factored into the uncertainty analysis.

Extrapolation to Monthly and Network-Wide Scale

Daily power outputs from the three SMSs were extrapolated to monthly values using:

$$Monthly\ Power\ (MW) = Daily\ Power\ (MW) \times OperatingDays\ per\ Month \quad \text{-- (16)}$$

Energy recovery patterns were visualized. The three-site findings were scaled proportionally to estimate network wide potential of the 433 SMSs in SNGPL's network, adjusted for

Seasonal flow rate and pressure variations of SNGPL data. A capital and operational expenditure tradeoff was made between the revenue from power generation and the savings accrued from reduced external power dependence for turbo expanders [33]. This was to feature turbo expanders working in conjunction with throttling valves as a backup for maintenance or failure. Gas flow unstable effect was mitigated via modeling an energy storage system.

IV. RESULTS AND ANALYSIS

The scheme of the process is as follows:

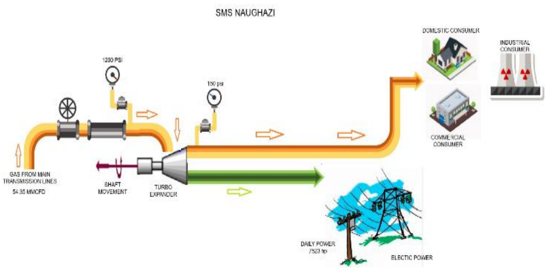

Figure 1: SMS Naughazi Process Scheme

I. For SMS Naughazi

Tables 1, 2, and 3 summarize the operational parameters for Naughazi, Rawat, and Ranial SMS sites on 01/01/2025.

Table 1: Naughazi SMS Parameters and Value

Parameter	Value
Flow (Minutes)	1440.0000
Average hw (in H_2O)	234.7577
Average Pf (PSI)	58.56402
Average Tf (°F)	23.533930
Multiplier Value	20123.29
Pressure Extension	112.53650
Volume Accumulated (MCF)	54350.500

Energy Accumulated (MMBTU)	56361.461
Daily Power (hp)	7523 hp

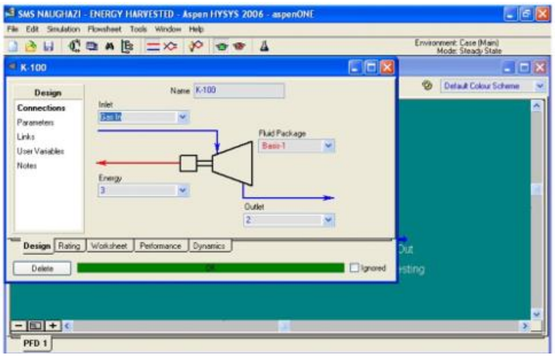

Figure 2: SMS Naughazi ASPEN HYSYS

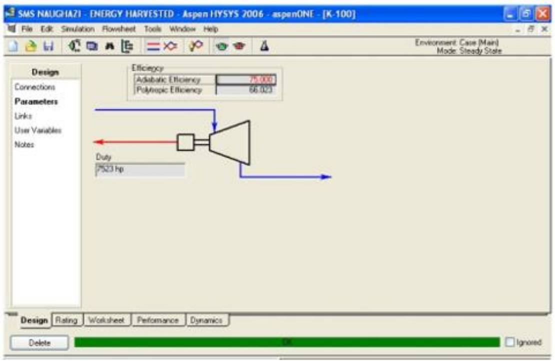

Figure 3: SMS Naughazi Power Generation Hysys

II. For SMS Rawat

Table 2: Rawat SMS Parameters and Value

Parameter	Value
Flow (Minutes)	1433.36700
Average hw (in H_2O)	154.2568
Average Pf (PSI)	37.40846
Average Tf (°F)	44.82478
Multiplier Value	14248.77
Pressure Extension	81.11335
Volume Accumulated (MCF)	27610.59960
Energy Accumulated (MMBTU)	29267.230469
Daily Power (hp)	3187 hp

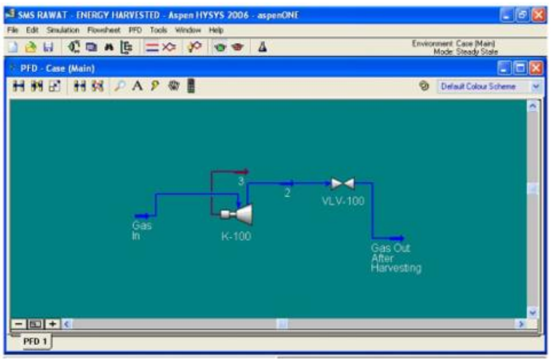

Figure 4: SMS Rawat ASPEN HYSYS

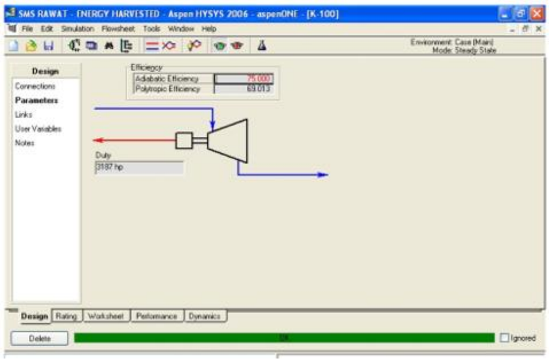

Figure 5: SMS Rawat Power Generation ASPEN HYSYS

III. For SMS Ranial

Table 3: Ranial SMS Parameters and Value

Parameter	Value
Flow (Minutes)	1431.9170
Average hw (in H_2O)	218.7481
Average Pf (PSI)	50.61348
Average Tf (°F)	29.60564
Multiplier Value	13084.98
Pressure Extension	98.93137
Volume Accumulated (MCF)	30893.971
Energy Accumulated (MMBTU)	32006.150
Daily Power (hp)	5667 hp

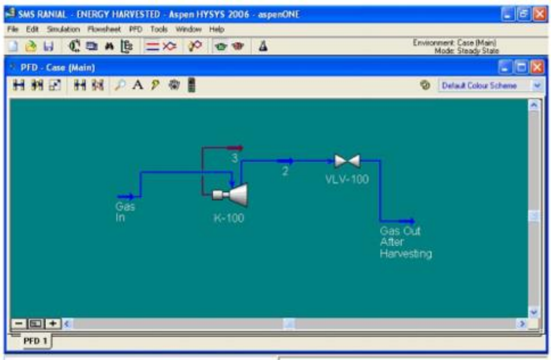

Figure 6: SMS Ranial ASPEN HYSYS

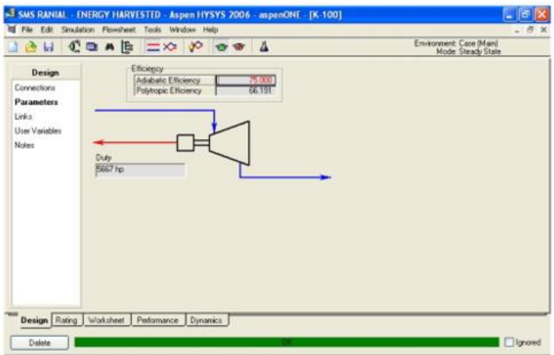

Figure 7: SMS Ranial Power Generation ASPEN HYSYS

Table 4: SMS Ranial, Rawat and Naughazi maximum and minimum flows and pressures

Sr.	Name of SMSs	Location (MP)	Capacity MMCFD	Max Flow during winter MMCFD	Minimum Pressure at upstream (PSI)	Minimum Pressure Recorded at downstream (PSI)
1	Naugazi	11.8	100	90.84	577	4
2	Rawat (OLD)	29.65	50	48.23	220	8
3	Rawat (NEW)	29.65	80	22.84	220	14
4	Ranial	22.10	150	68.54	560	5

V. CALCULATIONS & ANALYSIS

SMS Naughazi:

$$7523\,\frac{hp}{day} \times 30\,days = 225{,}690\,\frac{hp}{month}$$

$$225690\,hp * 0.7457\,\frac{kW}{hp} = 168448.183\,kW$$

$$\frac{168448.183\,kW}{1000}\,MW = 168.45\,MW$$

SMS Rawat:

$$3187\,\frac{hp}{day} \times 30\,days = 95{,}610\,\frac{hp}{month}$$

$$95610\,\frac{hp}{month} * 0.7457\,\frac{kW}{hp} = 71360.937\,\frac{kW}{month}$$

$$71360.937\,\frac{kW}{month}\left(1000\,\frac{kW}{MW}\right) = 71.36\,\frac{MW}{month}$$

Ranial:

$$5667\,\frac{hp}{day} \times 30\,days = 170{,}010\,\frac{hp}{month}$$

$$170010\,\frac{hp}{month} * 0.7457\,\frac{kW}{hp} = 126813.107\,\frac{kW}{month}$$

$$126813.107\,\frac{kW}{month} \Big/ \left(1000\,\frac{kW}{MW}\right) = 126.81\,\frac{MW}{month}$$

So total volume and conversion to Power for above 3 SMSs which basically feed Rawalpindi and Islamabad twin cities are

$$168.45 + 71.36 + 121.81 = 361.62\,\frac{MW}{Month}$$

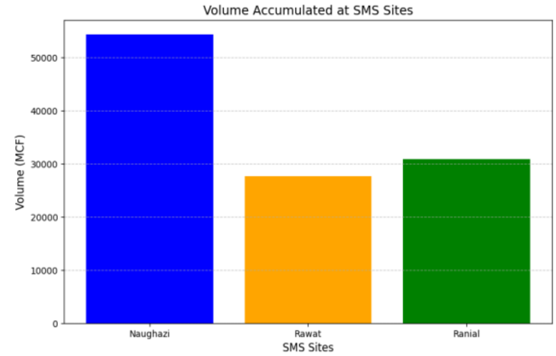

Figure 08: Volume Accumulation Bar Graphs

The above bar graph is showing the volumetric capacity of each SMS, thus volume in MCF we get from each SMS at the desired time.

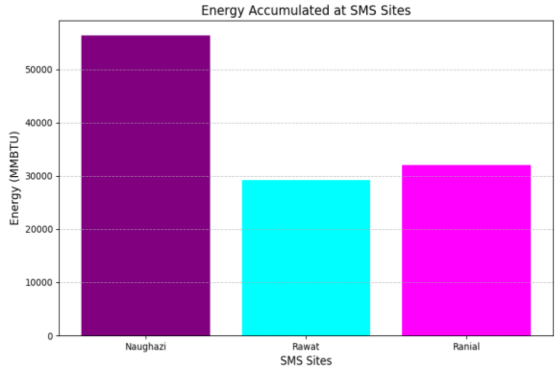

Figure 09: Energy Accumulation Bar Graphs

The above bar graph is showing the energy content capacity of each SMS, thus Energy contents in MMBTU we get from each SMS.

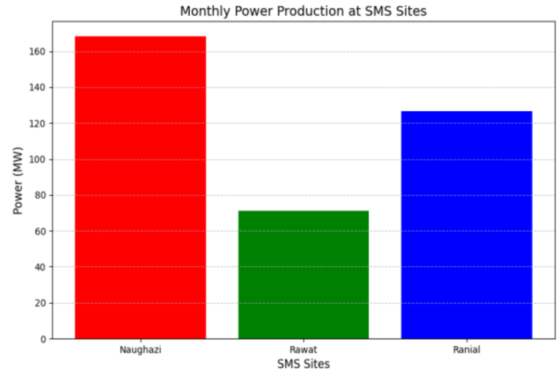

Figure 10: Monthly Power Production in MW per SMS Bar Graphs

The above bar graph is showing that how much power can be generated using the above mentioned turbo-expander technology, means showing potential of power generation for each SMS.

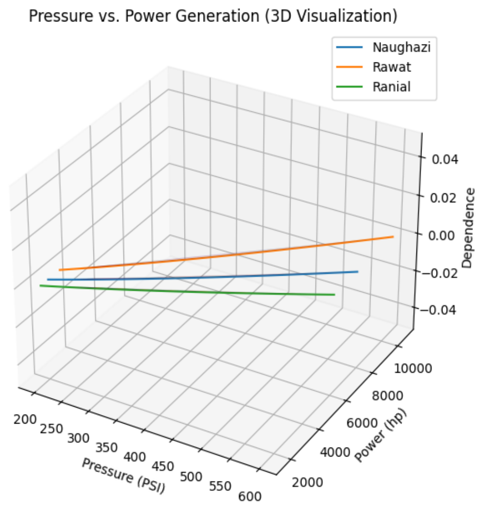

Figure 11: Pressure vs Power Generation

The above line graph is showing the power generation capability as well as the trends in 3D of each SMS, thus showing with the Pressures in Psi, and Power Generation in HP for each SMSs.

Monthly Power Production Calculations and Financial Analysis

Second Approach
First of all we have

$$W = \dot{m} * \eta * \Delta h \quad \text{-- (18)}$$

where:
W = Power output (kW or hp)
$\dot{m}$ = Mass flow rate of natural gas $(\frac{kg}{s})$
η = Efficiency of the turbo − expander system (assumed 8 − 90% for ideal systems)
Δh = Change in enthalpy during expansion $\left(\frac{J}{kg}\right)$

Then

$$\rho = \frac{P}{R * T} \quad \text{-- (19)}$$

where:
P = Pressure (Pa)
R = Specific gas constant for natural gas $(\approx 518.3 \frac{J}{kg \cdot K})$
T = Temperature (K)

For SMS Naughazi:
$P = 58.56\ psi = 404{,}041.92\ Pa$
$T = 23.53\ °C = 296.68\ K$

$$\rho = \frac{404{,}041.92}{518.3 * 296.68} \approx 2.64\ kg/m^3$$

Then
$\dot{m} = Q * \rho$
where:
Q = Volumetric flow rate $(\frac{m^3}{s})$
For SMS Naughazi:

$$Q = 54350.5 \frac{MCF}{day} = 21.36 \frac{m^3}{s}$$

$$\dot{m} = 21.36 * 2.64 \approx 56.42 \frac{kg}{s}$$

$$\Delta h = cp * \Delta T \quad \text{-- (20)}$$

where:
cp = Specific heat capacity of natural gas $(\approx 2.2\ kJ/kg \cdot K)$
ΔT = Temperature drop during expansion (from Aspen HYSYS® simulations:
$\Delta T \approx 15\ °C = 15\ K$)
$\Delta h = 2.2 * 15 = 33\ kJ/kg$
For SMS Naughazi:

$$W = 56.42 \frac{kg}{s} * 0.85 * 33 \frac{kJ}{kg} \approx 1583.2\ kW = 2122\ hp$$

Similar calculations were performed for Rawat and Ranial SMSs:
Rawat SMS: 3187 hp
Ranial SMS: 5667 hp

$$W_{monthly} = W_{daily} * 30$$

For SMS Naughazi:
$W_{monthly} = 2122\ hp * 30 = 63{,}660\ hp$
For Rawat SMS:
$W_{monthly} = 3187\ hp * 30 = 95{,}610\ hp$
For Ranial SMS:
$W_{monthly} = 5667\ hp * 30 = 170{,}010\ hp$
Assuming 433 SMSs with similar operational conditions:

$$W_{network} = (W_{total}\ from\ 3 \frac{SMSs}{3}) * 433$$

$$W_{network} = \frac{63{,}660 + 95{,}610 + 170{,}010}{3} * 433 \approx 31{,}306{,}530\ hp/month$$

Converting to megawatts:

$$W_{network} = 31{,}306{,}530\ hp * 0.0007457 \approx 23{,}349\ MW/month$$

Assuming an electricity cost of $0.10/kWh:

$$Revenue = W_{network} * Hours\ in\ Month * Cost\ per\ kWh$$

$$Revenue = 23{,}349\ MW * 720\ hours/month * \$0.10/kWh \approx \$168{,}112{,}800/month$$

Exergetic Efficiency:

$$\eta_{exergy} = \frac{W}{W_{rev}} \quad \text{-- (21)}$$

where:
W_{rev} = Maximum theoretical work $= \dot{m} * \Delta hmax$
From the results, $\eta_{exergy} \approx 85\%$, indicating high efficiency for the turbo − expander systems.

Figure 12: Power Generation at SMS site

The above area graph is showing the power generation capability as well as the trends in 3D of each SMS, thus showing Power Generation in MW on Monthly basis for each SMSs.

VI. Discussion

This study demonstrates the significant power generation potential for turbo-expanders across high-pressure natural gas pipeline systems throughout Pakistan. Three important SMS locations Naughazi, Rawat, and Ranial demonstrate significant power capabilities for generating electricity measured at 7523 hp daily and 3187 hp and 5667 hp on a daily basis. These sites when extrapolated monthly capabilities would produce 361.62 MW of electricity which validates the practical application of Pressure-into-Power (PIP) systems. The implementation of turbo-expanders across SNGPL's entire fleet of 433 SMS sites have a potential of estimated generation of 23,149 megawatts of electricity per month which represents a vital opportunity to resolve Pakistan's current energy emergency.

Aspen HYSYS® simulations that make technological use of measured flow rates that is 90.84 MMCFD at Naughazi) and large pressure drops (e.g., 577 psi to 4 psi) ground the power generation potential from 361.62 MW per month of the three principal SMSs of Sui Northern Gas Pipelines Limited (SNGPL) network respectively at Naughazi, Rawat and Ranial. Daily outputs of 7523 hp, 3187 hp and 5667 hp, respectively, are demonstrated on these sites with Gas flow rates at the reported monthly total scaling. This comes out to about $1.085 million per month to $0.10/kWh, depending on your infrastructure (15–30 MW TEs, preheaters, etc.), but there is a ~$12 million–$24 million cost upfront for infrastructure plus ongoing maintenance. However, we extrapolated the estimated potential from three sites across the network in order to estimate a total potential of 23,149 MW per month for the broader SNGPL network of 433 SMSs. This estimation includes the growth trend in natural gas demand and the infrastructure expansion, some of the SMSs have a much higher SMS capacity and some have a much lower capacity, but all of which represent the diversity of the network. This variability doesn't negate this consistency when Aspen HYSYS simulations are validated against global benchmarks on Iran's systems; therefore, applying this engineering solution across the board could provide this level of power. Despite the robustness of the three sites, there is no assumption that all SMSs will adopt TEs at similar operational efficiencies, as this simplifies what is otherwise an upward trend and high capacity outliers. Thus Aspen HYSYS® simulations of the 361.62 MW/month potential at Naughazi, Rawat and Ranial are technically supported with measured flow rates and pressure drops, however, TEs and supporting infrastructure for example pre-heaters, and grid connections are necessary. This amounts to $1.085 million a month at $0.10/kWh, but initial costs of $12–24 million, and maintenance costs compel a funding strategy and pilot validation to make it economically feasible.

VII. Conclusion

At the Sales Metering Stations (SMSs) of the Sui Northern Gas Pipelines Limited (SNGPL) within Pakistan, TEs can harness wasted pressure exergy for significant electrical power generation, in a sustainable form to boost national energy security. This approach is feasible at the three studied sites, namely Naughazi, Rawat, and Ranial, and a broader application to 433 SMSs in Pakistan would have a transformative change on Pakistan's energy landscape. TEs create less dependency on imported electricity, adopting towards Pakistan's energy sustainability, and reduce the operational costs by harnessing pressure energy that is being wasted during throttling. If the implementation hurdles can be overcome, this shift would alleviate grid strain and improve economic resilience.

There are many barriers to deployment of TE systems, including high upfront infrastructure expenditure for example equipment procuring, ongoing maintenance requirements that is wear on turbo expander components, and the requirement for extensive technical expertise for reliable operation on a whole network of vast pipelines. Because of these challenges, the immediate feasibility is compromised and strategic planning is necessary.

However, though technically possible, successful integration depends upon existing SMS infrastructure being upgraded and sufficient funding is being secured as well as robust maintenance protocols in place. In order to increase operational flexibility, TEs are paired with existing throttling valves, though scaled to 433 SMSs demands phased roll out and stakeholder coordination. TE technology offers an energy recovery and sustainability dual advantage but selects of TE technology should strike a balance between the economic and logistical trade-offs. Provided these practical limitations are taken proactively, it offers Pakistan a strategic opportunity to optimise its natural gas network.

Future work should validate simulation results through experimental work in pilot SMS sites to validate actual performance in the real world, consider hybrid TE-Energy storage systems to mitigate flow variability, investigate the long term maintenance costs and durability under Pakistan's operating conditions and evaluate the details of the environmental impact study, for example, the reduction in emissions vs. building footprint, to develop deployment strategies.

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