

UTILIZING TRANSIENT MODEL FOR SIMULATING UNCERTAINTY OF NATURAL GAS TRANSPORTATION SYSTEMS

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Abstract

High pressure fluctuations in gas transmission network is an extensive problem that leads to ineffective planning of gas management. Several studies are required to ensure pipeline integrity and safety limit remain intact. This paper investigates demand uncertainty factor and propose mitigation to solve high pressure fluctuation issue. A hydraulic steady state simulation is carried out using Pipeline Studio that computes time variant pressure output by considering flow, temperature and initial pressure profile for specific boundary and network element set points. Using sensitivity analysis result for gas flow equation and equation of state, the simulation is carried out for transient condition by using Movement Control Order (MCO) scenario due to pandemic COVID 19 as case study. Pressure trends obtained by running simulation on above case study are collected and compared with maximum operation pressure limit in pipelines. Result successfully concludes simulated pressure achieved is 61.87 barg with overall percentage of error by 0.31%. Study encourages future work to integrate simulation of gas and electricity to minimise uncertainty effect of gas demand to future proof the safety and reliability of pipeline system.

Keywords: Demand, Economic lockdown, Electricity, Uncertainty.

1. Introduction

Recently, gas supply chain has become one the most important aspects in energy industry. Sale gas is by far the most used in heavy industries mainly for electricity and power generation. Here, higher amount of energy release relies on the higher gross heating value as heat of combustion due to the presence of carbon compound in the gas molecule [1]. According to Ma [2], natural gas is the cleanest fossil energy and best fuel to be applied in industrial fuel mainly as a substitute for coal, transportation, distributed energy, power generation, and high-end natural gas chemical raw materials. The utilization of sale gas or dry gas is proven as an efficient energy combustor for high electricity generation besides low carbon footprint emission greenhouse gas [3] which meets Malaysian Carbon's reduction aspiration by 2030 [4]. In term of forecasted energy demand, it can be seen that the electricity demand keep arising from year to year due to developmental projects, construction of intercity railways and others. In order to meet future demands, the generation of reliable and continuous supply of energy shall be committed through enforcement of several policies, such as Four Fuel Diversification Policy (1981) [5], Five-Fuel Policy (2001) and Renewable Energy + Action Plan (2010) which emphasized on supply security, energy efficiencies and utilization as well as introduction of renewable energy [6].

On the other hand, authority strategy has designed to reduce overdependence on oil, with a push for gas as the major fuel in power generation. Renewable energy had subsequently been added under the Five-Fuel Diversification Strategy. Under the 10th Malaysia Plan (10MP, 2011-2015), the Government highlighted the New Energy Policy, which focuses on market pricing for gas and power, the diversification of supplies, as well as renewables and energy efficiency. The policy also aims to enhance energy security and reliability of supply through the development of renewable energy (solar, hydro, biomass etc) 25%, liquefied natural gas 40%, and coal 35% of total energy demand for power based on Green Technology Master Plan for Malaysia 2017-2030 [7] and APEC Energy Demand and Supply Outlook-5th Edition [8]. The policy also derives the security of electrical supply despite of gas depletion from offshore wells to achieve a balanced fuel mix in electricity generation, which goes towards ensuring energy security, affordability, and stability.

In accordance with this, Energy Commission has declared the Energy Mix Policy which clearly states that future energy supplies from gas and coals would be reduced due to national commitment on carbon dioxide reduction to atmosphere and dependency on conventional sources. Study reveals lowest percentage of gas consumption for power generation is 30% from the total energy mix in European country [9] It is proven that grid network planning would still require gas source on power generation due to described benefits of sale gas. This situation would have encouraged utilization of renewable energy such as hydro, waste products, and nuclear sources as options to be developed starting 2022. Despite of stated difficulties and challenges, prudent gas transporter has to assure the ability to remain relevant and competitive in domestic and international market by exceptionally responding to volatility, uncertainty, complexity and ambiguity world (VUCA) of gas supply demand scenarios and increasingly sophisticated customer demand.

The rationale in adopting scenario planning to bring down dependency on traditional predictions resulting to failure can be related to the severe oil price drop in 2015 whereby some countries still practiced an excessive reliance on income from

oil export, and unforeseen global COVID-19 pandemic outbreak occurred in 2020. If the management had engaged on scenario planning, perhaps they could realign company decision to other strategic directions which would save the country from crisis. In addition, Benedict [10] said that scenario planning arose from a recognition that one could not predict the future with any accuracy at all due to limitation of users. Problems that include uncertainty mainly focus on plant design, plant planning or scheduling, and supply chain. There are several applications of modelling with uncertainty issue from literature adaptation especially on planning and scheduling of natural gas.

1.1. Planning and scheduling

The planning or scheduling of the supply chain under uncertainty is important considering the ever-changing market conditions [11]. Due to existence of considerable lead times (the difference between the request and fulfilment times of an order) in the supply chain, the production variables must be determined prior to the demand realization. The challenge is how to set optimal operating strategies to maximize the profit with satisfactory customer service levels. Gupta and Maranas [12] studied supply chain planning using two-stage programming. Inventories were considered in the model, and penalty terms were used for stock-out or inventory levels that are too low. In their approach, the penalty terms (such as a safety stock violation penalty) were difficult to estimate. Applequist et al. [13] introduced a new metric for evaluating supply chain design and planning risk under uncertainty whereby a rational balance between the return and risk can be obtained.

According to Shah [14], supply demand planning is a tool to optimize transportation of products from the suppliers to end users based on nominations over a period of gas day. For any industries, integrated planning is essential to provide low transportation costs and meet customer satisfaction through continuous service and support [15]. The work also mentioned that transportation planning is commonly discussed under short short-term planning in order to optimally dispatch gas to end users' demand efficiently. However, majority gas transporters practiced short- and long-term planning altogether with respect to company business strategies. Facing the outline direction of supply demand planning, Benjamin [16] investigated the choice of transportation method with multiple suppliers, customers and single product on high pressure system.

Ríos-Mercado and Borraz-Sánchez [17] mentioned in their research on rough idea of method selection to solve optimization problem in term of planning including line-packing, gas quality problem, cost minimization of fuel and compressor location. The study includes consideration of transient and steady state model which implies to real life industrial application and solution methodologies in assisting decision making process. Liu et al. [18] also commented under steady state behaviour, minimum cost of energy can be achieved by adopting optimal rule into the model. Other than that, Ierapetritou and Pistikopoulos [19] studied planning problems on transmission expansion and effect of energy consumption with effective design of long-distance pipeline [20].

On the other side, planning requires data input from customers to enable gas transporter in nominating volume of gas to suppliers. Thus, gas transportation business is depending on gas demand hence enabling company to charge on transport cost, operation, and maintenance cost of the facilities. To have an effective scenario

planning, the planner should know the demand behaviours on short- and long-term basis. For example, on power sector industries, gas demand is influenced by electrical generation performance. Historically, when electricity is highly demanded, gas consumption would be high. Few researchers conducted a study on correlation between gas and electric generation [21] and outlined a significant improvement on hourly economic demand response for enhancing the scheduling coordination of electricity and natural gas networks.

Meanwhile, Erdener et al. [22], performed a study on integrated simulation model for analysing electricity and gas systems resulting in significant finding of dependency of each other in term of gas fired power plant and electrical driven compressor. Throughout simulation analysis, the team found that cascading effect of dynamic system would be less effective than internal effect of individual system. Thus, dynamic system of gas and electricity have slower influences which draw to system disruptions due to presence of inventory with individual time frame. The author simulates different view when it comes to coal performance due to reliability factor. In view of this, coal plant reliability is much lower than gas plant reliability. The frequency of coal plant trip is more likely to happen compared to gas plant.

According to Reed [23], ultra-supercritical coal plant can only generate 60% of its capacity compared to usual at 80% and this would be resulting to unfriendly environment to electricity market when gas supply interrupt, conventional coal plant often cannot response fast enough to serve as back up of the electricity imbalance. Figure 1 shows the yearly distribution of power sector electricity fuels performance. Majority of consumption is from coal (53.75%), followed by gas (40.22%) and others (6.03%). With response to the above fact, another study from Kumar et al. [24] reveals that switching of electricity generation fuel from coal to natural gas is not cost effective due to pricing factor of natural gas and regulatory of environment commitment as well as creating high buffer to accommodate the loss of mega joules of electricity supply. The author also found commitment of power producer in stabilizing national grid electricity which derive decision to switch to natural gas once plant tripping scenario occurs. For instance, one trip or emergency outage coal generation of 1000MW can cause additional volume of 170 mmscfd natural gas demand and this would prolong to certain days depending on volume of electricity production loss and the seriousness of unplanned shutdown case. This uncertainty causes high pressure fluctuations at several location, pipeline hydraulic impact and equipment reliability issues at pipeline network as the design which deviate for intended design of having constant flow and tolerable pressure differences.

Above all, scenario planning has been studied recently. Majority of the reported research have focused on minor system optimization even though planning tools are established among planners, however the planning and inventory management levels have a lack of extensive mathematical approach to describe the overall plant operation [26]. Nevertheless, plant engineers are expected to be able to perform either online or offline real time and forecast simulation independently. Regardless of this, the use of manual calculation is still practical to reduce dependencies of available simulation and optimization software with reasonable end results especially during software downtime period for the second choice of decision making. Thus, effective scenario planning of gas supply demand scenarios would impose a good company reputation because of zero gas curtailment to end users, zero customer complaints and high transportation reliability and availability. These are important key parameters in becoming a world class gas pipeline operator.

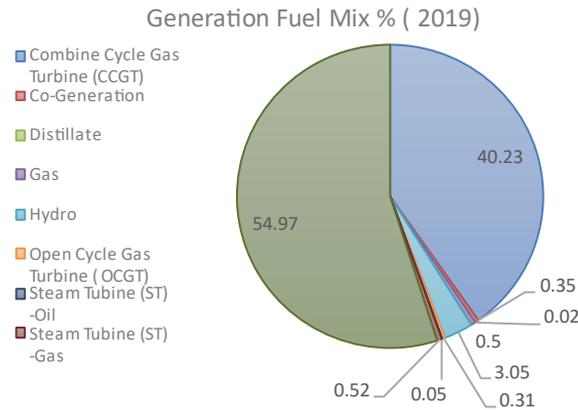


Fig. 1. Peninsular Malaysia Generation Fuel Mix 2019 [25].

To come out with reliable planning work, an appropriate task to develop systematic model or advanced engineering tool is essential to assist decision making process across the business supply chain. A prospective method is to utilize scenario-based approach of gas transmission network, for planner to reflect effective on supply demand planning which takes demand uncertainty, i.e., total economic lockdown and inventory management into account. This will be a better management of high-pressure fluctuations in pipeline system due to locations of gas supply point, pipeline hydraulic constraints and undistributed of gas offtake location.

In short, this study aims to study and assess demand uncertainty, formulate demand and supply input into pipeline simulation models and solve the problem based on given case study. Some basic theories and selection of gas equations are shown to complement this study.

1.2. Basic theory

At present, the progress of pipeline technology has been developed to solve the nonlinear equations starting with the Hardy Cross method in 1936, whereby in late 1950s, hydraulic calculation for pipeline network is introduced [27]. In addition, steady-state gas network simulation is derived to solve pipeline equations by using linearization theory [28]. In twentieth century, digital technology undergoes faster development to respond with industry pain points. One of them, is a gas pipeline simulation software by Emerson which is widely known software as Pipeline Studio for Gas TGNET [29]. This software is capable of running both transient and steady state simulations which suit a scenario-based approach method for this study. Considering a single-phase gas flow pipeline with turbulent flow regime and steel pipe material, actual operation of gas transmission system is modelled via Pipeline Studio. TGNET software mainly consists of Sarem, Peng- Robinson and BWRS equation [30].

The gas velocity inside pipeline is normally limited; either to reduce erosion or noise, and to ensure flexibility of valve throttling. Hence, it is crucial to define the correct choice for equation of state and gas flow equation in this study towards a clear understanding of the situation.

Sarem equation of state [29]

Sarem equation comes with variables of area, pressure and temperature in each pipeline network. The Sarem Z factor correlation is a corresponding states polynomial curve fit to the charts published for sales gas compressibility as a function of reduced pressure and temperature. Reduced pressure and temperature values are determined based on approximate correlations for pseudo-critical pressure and temperature (based on gas gravity). This equation enables user to customize gas properties. Once gas compressibility has been determined, the corresponding gas density is calculated directly using the ideal gas law corrected for compressibility. However, the equation is not suitable for distribution network where line pressure is lower than 20 barg due to large error identified.

$$Z = \sum_{m=0}^5 A_{mm} P_m \left(\frac{2P_r - 15}{14.8} \right) P_n \left(\frac{2T - 4}{1.9} \right) \quad (1)$$

Peng-Robinson state equation [29]

The Peng-Robinson equation is known as cubic equation in pipeline simulations due to the formulation. The non-linear formulation of Van der Waals considers effects of temperature and conic curve of real numbers. It is developed on the basis of SRK equation and expressed in term of critical properties and acentric factor.

$$P = \left(\frac{RT}{v-b} \right) + \left(\frac{a\alpha}{v^2 + 2bv - b^2} \right) \quad (2)$$

where

$$a = 0.45724 \frac{R^2 T_c^2}{P_c} \alpha, b = 0.07780 \frac{R T_c}{P_c}, \alpha^{0.5} \\ = 1 + (1 - T_r^{0.5})(0.37464 + 1.54226\omega - 0.26992\omega^2)$$

BWRS state equation [31]

The BWRS equation of state contains eight important parameters which is applicable to both phases of gas and liquid.

$$P = \rho RT + \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T_3} - \frac{E_0}{T_4} \right) \rho^2 + \left(bRT - a - \frac{d}{T} \right) \rho^3 + \\ a \left(a + \frac{d}{T} \right) \rho^6 + \frac{c\rho^3}{T^2} (1 + \lambda p^2) e^{-rp^2} \quad (3)$$

The state of equation acknowledges hydrocarbon and non-hydrocarbon gas elements, which incorporates virial coefficients depending on temperature and gas components. Despite its complexity and in-depth computation, this equation of state has been shown to be applicable over a wide range of pressures and temperatures for hydrocarbon fluids. The BWRS Equation of State can be solved implicitly for gas density, using a numerical technique.

Gas flow equations

Determination of gas flow equation depends on the alignment with actual pipeline condition. The flow is generally the same except for its friction factor. It highly depends on exact flow behaviour in the transition region between laminar and turbulent flow. Thus, friction factor will be based upon Reynolds Number classification.

AGA equations [31]

This equation is derived for turbulent flow of low flow and high flow rates. Friction factor is set as constant multiple of drag factor. The high velocity turbulent flow is given as below:

$$Q_{st} = 38.77 \frac{T_{st}}{P_{st}} \left[\frac{P_1^2 - P_2^2 - 0.375G(h_2 - h_1) \frac{P_{avg}^2}{z_{avg} T_{avg}}}{GLT_{avg} z_{avg} T_{avg}} \right]^{0.5} X \left[4 \log \frac{3.7D}{k_e} \right] X D^{2.5} \quad (4)$$

Colebrook-White Equation [31]

This equation combines three flow regimes; partially turbulent, transition and fully turbulent. This equation is modified on constant number to achieve better agreement with experimental data at higher Reynolds numbers and consequently the flow equation will be

$$\dot{Q}_{st} = 13.2986 \frac{T_{st}}{P_{st}} \left[\frac{(P_1^2 - P_2^2) - E}{L d T_{avg} z_{avg}} \right]^{0.5} - \left[2 \log_{10} \left(\frac{\epsilon/D}{3.7} + \frac{2.825}{Re \sqrt{f}} \right) \right]^1 D^{2.5} \quad (5)$$

Weymouth Equation [31]

This equation is derived based on transmission factor and consideration of pipe diameter. It is frequently used in design of pipeline distribution network with consideration of pressure drop calculation. Thus the equation is formed as,

$$\dot{Q}_{st} = 137.2364 \frac{T_{st}}{P_{st}} \left[\frac{(P_1^2 - P_2^2) - E}{L d T_{avg} z_{avg}} \right]^{0.5} D^{8/3} \quad (6)$$

1.3. Sensitivity analysis and methodology

In order to identify the most suitable equation on this model for equation of state and gas flow, two cases are selected; normal and abnormal operation. For normal operation, network transmission resumes as a balanced system whereby total gas in is equal to total gas out with 2100 mmscf sales gas. For abnormal operation, network system experiences imbalance whereby total gas out used is 2200 mmscf and total gas is 2100 mmscf respectively.

The process requires important parameters of data inputs such as inlet pressure and temperature change due to frictional loss, gas velocity and Joule-Thompson effect. Gas composition, standard temperature and pressure are also included and other inlet of pipeline specifications prior to run the simulator. It will internally divide each pipe into segments based on user's specified nominal distance step. Equation of state will calculate pressure based on real gas law and compressibility factor as provided earlier. Then, selected gas flow equations will solve calculation of data input and given pipeline specification accordingly at each pipeline segment in view of turbulent flow and Reynolds numbers. The resultant set of equations are first order in time and second order in space. Gas composition tracking is performed using batch tracking method and at nodes where mixing occurs, gas compositions are blended using the specified mole-averaging rule. The mole fraction number will be related to molecular weight and density of gas. Hence, based on the flow equation, potential energy term E, is considered by having relative density, elevation, pressure, temperature, and compressibility factor. Pipeline studio simulator will run the models accordingly. This process is shown in Fig. 2.

Table 1. Pipeline transportation condition for sensitivity analysis.

Gas Composition [32]	Mole percent Lean (%)	Mole percent Rich (%)
Methane	94.9	84.04
Ethane	2.24	4.95
Propane	0.24	1.62
Iso-Butane	0.05	0.12
N-Butane	0.04	0.07
Iso-Pentane	0.01	0.07
N-Pentane	0.04	0.03
N-Hexane	0.03	0.03
Nitrogen	0.85	1.59
Carbon Dioxide	1.51	7.48
Transmission condition	Total Pipeline Length: 2273 km, Inventory: 17.76 mmscf Temperature: 27 °C, Pipeline diameter (inch): 36 Pipeline efficiency: 1	

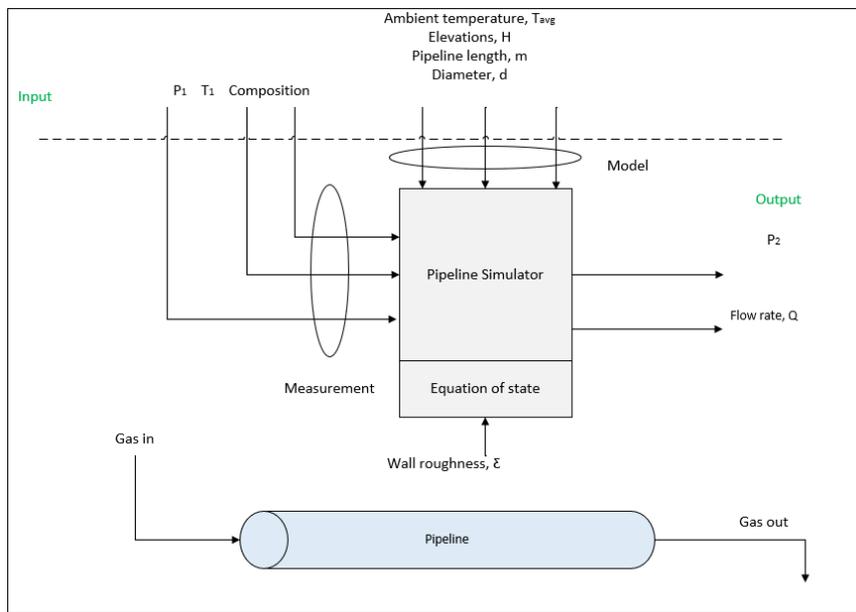


Fig. 2. Illustration of network model methodology.

Table 2. Resultant speed with different equation of state and gas flow equation for normal operation.

Network speed (m/s) performance under normal operation						
Equation of state	Gas Flow equation			Percentage of error %		
	AGA	Colebrook	Weymouth	AGA	Colebrook	Weymouth
SAREM	0.51	0.53	0.54	1.92%	0.02%	0.04%
Peng Robinson	0.53	0.54	0.54	1.92%	3.85%	3.85%
BWRS	0.52	0.54	0.55	0.00%	3.85%	5.77%
Initial speed	0.52	0.52	0.52			

Table 3. Resultant output pressure with different equation of state and gas flow equation for normal operation.

Network pressure (barg) performance under normal operation						
Equation of state	Gas Flow equation			Percentage of error %		
	AGA	Colebrook	Weymouth	AGA	Colebrook	Weymouth
SAREM	50.5	49.17	48.26	0.50%	2.15%	3.96%
Peng Robinson	50.14	48.79	47.86	0.22%	2.91%	4.76%
BWRS	50.31	48.97	48.05	0.12%	2.55%	4.38%
Initial speed	50.25	50.25	50.25			

The variations in trend of speed and output pressure based on three state of equations and three gas flow equation are shown in table 2 and 3 respectively. Each result is compared with initial data input in term of speed and pressure. It is observed that the smallest percentage of error 0.00% occurs when BWRS as equation of state is used under AGA gas flow equation on resultant speed of 0.52 m/s. Similarly, resultant speed profile favour on the same set of equations gives 0.62 % percentage of error when compared to 50 barg input pressure. When using the “SAREM” and “Peng Robinson” state equation, calculated percentage of error result are 1.00% and 0.28% on resultant pressure and 1.92% for both on resultant speed respectively for normal operation. For other than pairing of AGA and BWRS, resultant pressure and speed with respect to initial value is relatively higher due to limited consideration of friction factor and pressure drop.

Table 4. Resultant speed with different equation of state and gas flow equation for abnormal operation.

Network speed (m/s) performance under abnormal operation						
Equation of state	Gas Flow equation			Percentage of error %		
	AGA	Colebrook	Weymouth	AGA	Colebrook	Weymouth
SAREM	1.74	1.83	1.9	1.51%	3.58%	7.55%
Peng Robinson	1.79	1.87	1.95	1.32%	5.85%	10.38%
BWRS	1.77	1.85	1.93	0.19%	4.72%	9.25%
Initial speed	1.77	1.77	1.77			

Table 5. Resultant pressure with different equation of state and gas flow equation for abnormal operation.

Network pressure (barg) performance under abnormal operation						
Equation of state	Gas Flow equation			Percentage of error %		
	AGA	Colebrook	Weymouth	AGA	Colebrook	Weymouth
SAREM	43.63	41.75	40.17	0.30%	4.02%	7.66%
Peng Robinson	43.15	41.24	39.62	0.80%	5.20%	8.92%
BWRS	43.39	41.5	39.9	0.25%	4.60%	8.28%
Initial speed	43.5	43.5	43.5			

In abnormal operation, selection of AGA as gas flow equation and BWRS as equation of state produces lowest percentage of error compared to other component matching as in Table 4 and Table 5. Accordingly, Weymouth equation is most frequently used for distribution networks despite being less accurate than other equations due to overestimation of the pressure drop calculation in normal and abnormal operations. Colebrook equation has limited consideration of Reynolds numbers from 2000 to 2×10^6 on friction factor, which similar result to AGA partially turbulent [33, 34].

Thus, BWRS state of equation and AGA gas flow equation are recommended in the calculation of steady state and transient simulation of high pressure and turbulent natural gas flow transmission system in Peninsular Malaysia. This is in line with research conducted by Ren et al. [35] which outline both BWRS and AGA have the best precision in which deviation is less than 1 % and able to meet the requirement of engineering calculations. In term of practical limitations for natural gas pipeline less than five barg, using copper and polyethylene pipes, typical flow will be partial turbulent and pipeline roughness is not required for consideration. However, for steel pipeline and high-pressure pipeline, the existence of turbulent flow is commonly applied which must consider the influence of internal pipe roughness. Hence, utilization of AGA is adequate due to its simpler nature and satisfactorily translates the change of transition from partially to fully turbulent flow [36].

2. Analysis of Peninsular Malaysia Energy demand

Peninsular gas demand is heavily depending on industrial sector with expected demand growth, as outlined in Fig. 3. Based on historical update (2015-2019) overall energy demand growth at 2.5% per annum equivalent into 16,822 MW -18566 MW respectively, according to energy latest forecast, is expected to growth at 1.8 % per annum at based Malaysia Generation Development Plan (2019-2030) [37].

2.1. Demand and supply projection 2010-2050

Based on studies conducted by Allan [8] and Report on Peninsular Malaysia Generation development plan [37], renewable energy is introduced to cater long term additional demand projection and to replace non-renewable energy source. Throughout potential additional energy demand study per sector by Haiges et al. [38] with expected growth rate as per Malaysia Energy Commission data, industry sector is the biggest contribution with expected increment of 4.4 % (2013-2020), 1.8% (2021-2025), and 1.4% for (2026-2035) and (2036-2050) respectively.

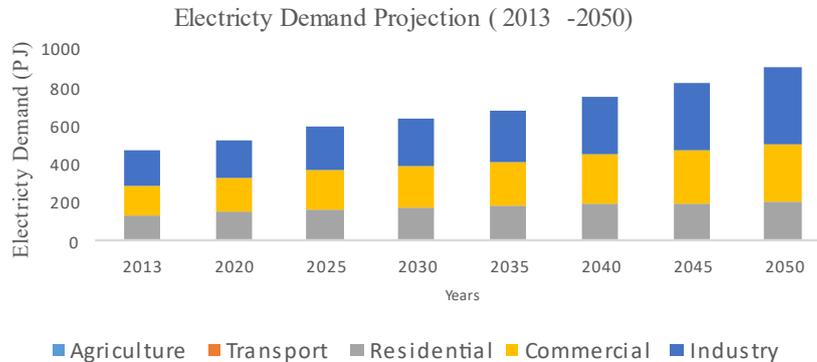


Fig. 3. Electricity demand projection (2013-2050) [32].

In 2020, about 500 MW of Renewable Energy (RE) has been installed at Peninsular Malaysia under a large-scale solar farm project in capacity of 459 MW. The authority aims to increase by 2172 MW of renewable energy by end of 2025. Thus, RE will compromise total demand requirement of distribution network, whereby expected net demand will grow at 0.7 % per annum for the next 11 years.

This basis will be used for supply mix framing as tabulated in Figs. 4 and 5. Accordingly, expected supply mix generation from RE will increase from 9% to 30% by the end of horizon to support country sustainability agenda for cleaner energy, diversify energy power fuel mix and reduce greenhouse emissions [39]. Meanwhile, generation of coal is expected to drop in 2027 due to retirement of plants and replaced by RE and portion of natural gas. Installed capacity will be based on demand projection and overall gross domestic product.

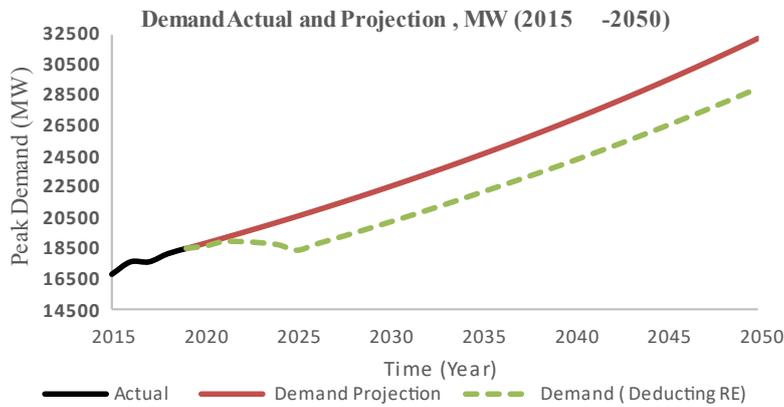


Fig. 4. Demand actual and projection MW (2015-2050) [32].

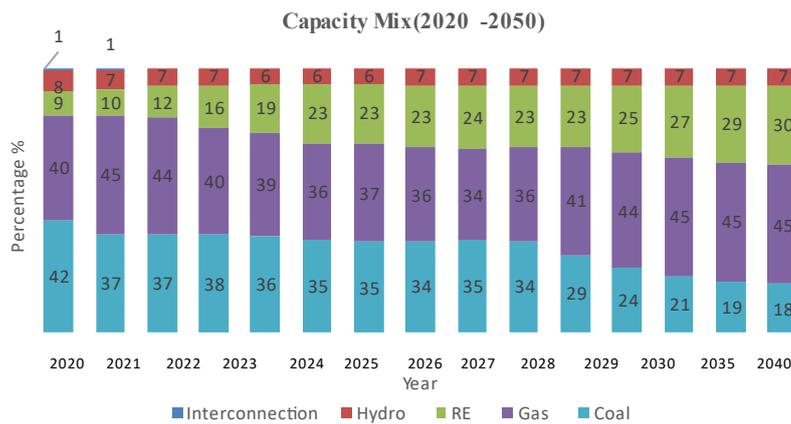


Fig. 5. Supply Mix Projection % (2020-2050) [40].

2.2. Malaysian grid code

Apart from demand projection and fuel mix policy, the Malaysian Grid Code is established as an instrument to coordinate electrical supply activities from various fuel mix, including the transmission, distribution and consumer. It is a fair treatment imposed by the government to ensure reasonable tariff for electricity to end users. Grid is upholding the principal of least cost operation in term of dispatching, generation, and scheduling [41]. Responsible party namely Single

Buyer (SB) will purchase electricity from generators based on a least-cost approach, in a way that the lowest marginal cost generating unit is dispatched primarily and continue with the next-lowest marginal cost generating unit, until all electricity demand is met and tied with merit order concept on renewable energy. The buying concept is practically consistent with requirement of Generator Contracts, Daily Heat Rate, and Variable Operating Rate Bids [40, 41], as required under related single buyer market rules. On the other hand, Grid Supply Operator (GSO) will conduct real time assessment on overall gridline requirement to ensure system stability and report cost of operation based on this code to Energy Commission. Under this operation, GSO will control real time generation of electricity demand based on several fuel mix based on least cost operation as per Fig. 6. Least cost operation includes net cost of operation to produce kilowatt hour of gas per unit price. Renewable energy sources such as solar and hydro impose cheap unit cost compared non-renewable fuel source. This arrangement will be impacting the management of gas planning during abnormal scenario such as pandemic COVID-19.

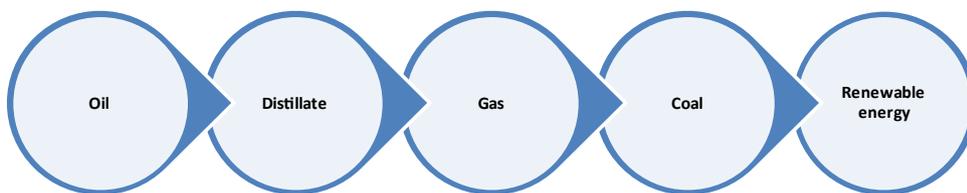


Fig. 6. Historical data analysis based on least cost operation [41].

It is observed that dependency of fuel mix for electricity generation from one to another will need major alignment of scenario planning. Internal and external factors such as pricing impact [42], frequent change of weather season, peak demand uncertainty [43] and reliability issue [44] of power plants will cause uncertainty planning towards gas transmission network. The following section will discuss more on the impact to gas segment.

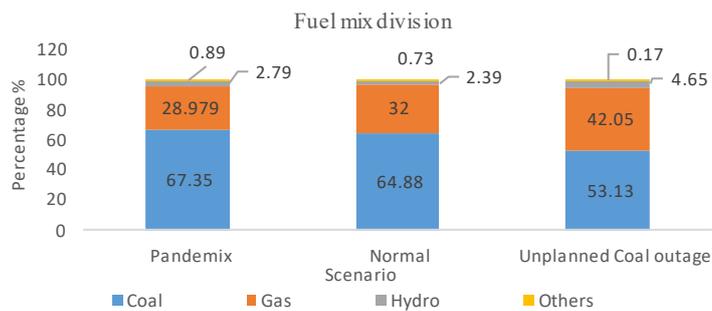
2.3. Analysis of historical gas demand during normal situation vs. during total economic lockdown

As primary fuel, natural gas is used for transportation, commercial and domestic uses, petrochemical plants, as well as large and small industries. Below table illustrates the overall sales gas delivery to domestic market. As acknowledged, reduction of domestic demand is due to the increase of coal production for electricity generation to ensure Malaysia's energy security [45] and development of renewable energy, under 11th Malaysian Planning, which aims to diversify fuel mix to support growth initiative in Malaysia. Therefore, gas producers are able to accommodate national gas demand which aligns with domestic gas reserve available. In 2019, slight increase of gas demand recorded due to commissioning of Refinery and Petrochemical Integrated Development (RAPID) Project. However, the slight decrease of domestic sales gas is due to global pandemic of coronavirus disease 2019 (COVID-19) and post fire incident which led to a shutdown, in March 2020 at a diesel hydrotreater unit [46]. Based on the above factors, sales gas consumption has dropped to 1900 mmscfd in Peninsular area as per Table 6.

Table 6. Sales gas consumption at Peninsular Malaysia.

Year	Sales Gas Consumption (MMscfd)	Source
2014	2322	[47]
2015	2225	[48]
2016	2152	[49]
2017	2061	[50]
2018	2060	[51]
2019	2272	[52]
2020	1882	[53]

The unprecedented decline in total energy demand has caused energy sectors to re-strategize their scenario planning in preparation of complicated impacts and to identify emerging opportunities. Since natural gas is mainly used for electricity generation, COVID-19 has increased the uncertainty of electricity demand [54], posing high pressure on pipeline gas operators [55]. The Malaysian government starts to impose Movement Control Order (MCO) in view of increasing local COVID 19 positive cases, especially at Peninsular area, on 18th March 2020 as well as to provide sufficient time for public health sector to prepare in facing new pandemic situation. This order is considered a total economic lock down whereby necessary sectors such as public, commercial, transportation and industrial are strictly controlled for minimum operation. In this event, essential businesses are allowed to operate with minimum work force and strictly adhere to Standard Operating Procedure approved by Ministry of International Trade and Industry. Figure 7 shows situation of gas-electric performance pattern prior and during MCO enforcement.

**Fig. 7. Supply mix division under 3 different scenarios [41].**

Overall electricity demand started to drop on the day of MCO declaration, correspondingly from 16500 MW to 11500 MW. This also impacts the overall fuel or supply mix to change and accommodate new low electricity profile. Figure 8 observes the most impacting fuel mix is sales gas whereby it is being sandwiched compared to normal operation. On other fuel mix perspectives, utilization of coal and hydro are increasing compared to normal operation due to least cost of operation as stipulated in the grid code, renewable energy factors as it will consider all the maximum demand and new capacity installed for coal portion as approved by Commission. Reduction of 30.21% in gas demand shows consistent new low level of gas requirement at 4000-5000 MW until MCO is lifted in 31st May 2020 as per Fig. 9. Additionally, 30% reduction of electricity demand significantly impacted gas production due to deviation of actual gas consumption which causes high pipeline inventory system.

Under the case of abnormal operations, gas remains as a reliable fuel supply to accommodate overall electricity demand in Peninsular. Scenarios of unplanned outage and constraints from other fuel generations shows that the portion of gas utilization increase to 42% of overall fuel mix production. Increase of gas subsequently require planning of gas from liquified natural gas terminals and piped gas to maximum operation. In the event of low gas pressure in pipelines, other fuels will be maximized in the sense of allowing shipper to inject sales gas volume to refurbish inventory losses, until gas pipeline pressure is normalized.



Fig. 8. Peninsular gas utilization network [52].

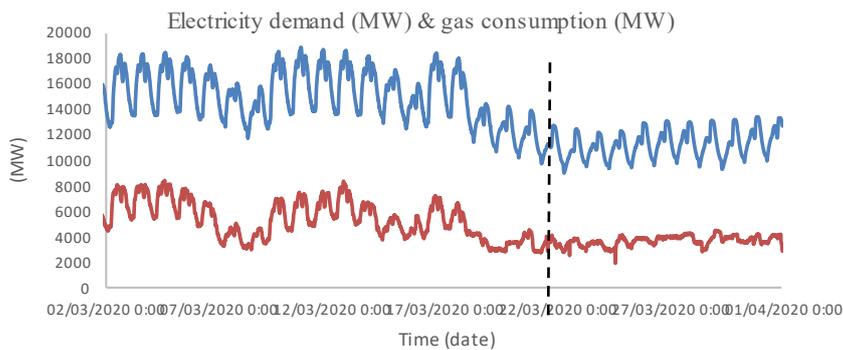


Fig. 9. Electricity demand and gas consumption [41].

3. Simulation Prediction on Pipeline Network System

The transportation of gas from entry points to exit points possess a significant role in between the shipper (Seller) to the customers of sale gas (Buyer). The sales gas agreement between seller and buyer is essential towards utilization of gas pipeline network for long term commitment. Currently, four (4) nodes of supplies are connected to pipeline network. There are two (2) nodes from processing plants and two nodes on liquefied natural gas (LNG) terminal whereby regasification of LNG into dry gas process take place and injected into the network as shown in Fig. 9. Typical gas quality is considered into the network pipeline and basically stipulated in transmission code. The sales gas or methane gas would be transported to pack pipeline inventory via compressor stations and received by end users. The facility of transmission including metering stations of each supplier and end users, supervisory control, and data acquisition (SCADA), block valves analysers and catalytic protection systems mainly for billing purposes, network real-time monitoring and pipeline integrity program. On the demand side, there are three (3) categories of customers which are power sectors, export, and non-power users from the total demand. To operationalize integrated gas planning and as per global practice, pipeline operator will adopt prediction model to simulate accurate gas planning in term of balancing, inventory portfolio and internal gas consumptions. Apart from the brief theory on the pipeline simulator in Section 1.2, normally planner will run the simulation based on amount of transported gas supply and demand. Taking into consideration existing inventory in the pipeline, simulated result is presented in term of pressure profile and monitored on strategic locations based on planner assessment. Pipeline Studio is also used for shutdown maintenance works such as compressor operational repair work, pipeline hot tapping, derating, sizing and designing of new pipeline lateral.

There are three (3) points registered as S1, S2 and S3 in pipeline network. Each of the points represent individual sector of total demand centration. Execution of simulation for weekly profile will be shared to shift operation for real time monitoring and response if major deviation is identified. On weekly basis, inventory is gradually decreasing on weekdays and increasing again on weekends for packing as indicated in Fig. 10 for typical simulated pressure profile. High pressure of the pipeline system is considered as high inventory which aiming to prepare pattern of demand fluctuation due to gas supply constraint to follow dynamic demand. In this system, pipeline network is being considered as the gas storage due to unavailable storage tanks constructed along the network. The means of storage in this view would be temporary storage via linepack. In normal condition, high gas consumption during office hour is due to work commitment which utilizes high electrical consumptions for all sectors and slight lower during weekend and non-working day. In case of any supply shortfall or upsurge from suppliers or customers, gas transporter will monitor system imbalance and perform necessary action to rectify the gas transportation process. In term of gas supply, particular arrangement of linepack utilization will avoid gas supply to need major adjustment of gas send out based on weekly planning. As such, pipeline gas transporter will be able to manage associated constraints like production, operational (operating pressure) and equipment limitation.

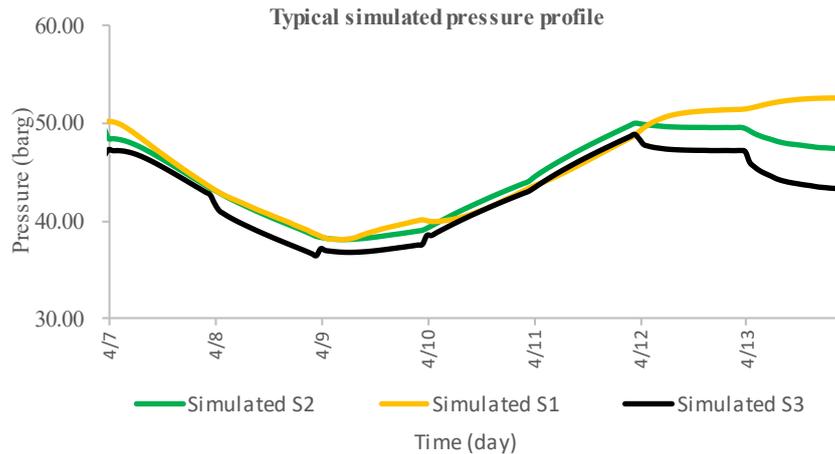


Fig. 10. Typical simulated pressure profile.

4. Results and Discussion

The prediction and forecasted pressure profile is presented in the following structure of case study. There are two case to be considered. (I) Transport planning before MCO declaration and (II) Transport planning during MCO period which translated into total economic lockdown for Peninsular Malaysia by using Pipeline Studio software.

4.1. Simulation profile prior and during MCO declaration

For the above case, planner used to run the simulation on 16th March 2020, on usual weekly pressure profile. By using a firm set of demand numbers and inventory as reference, simulated pressure for respective place for S1, S2 and S3 are tabulated in the respective graph of Fig. 11 with optimum compressor running speed. The assumptions are made based on the latest available information from respective customers. Upon study of the profile, it is shown that forecasted S1 and S3 are overlapping each other due to high concentration of demand, which are lower opening pressure compared to S2. However, it is noticed that negative imbalance is identified starting 18th March 2020 on 00:00 hours of power sector gas demand, as it dropped on the range of 5820 MW to 4520 MW respectively as in Fig. 8. Thus, pressure at points S2 and S3 slightly increased which causing high rate linepack build up and high network inventory.

S3 node is the highest pressure due to low demand utilization, followed by S2 and S1. Upon verification, it is due to impact of unprecedented low demand from power, industrial and commercial sectors due to economic lockdown under MCO. Additionally, it is observed that northern gas plant generators stop consuming gas as the total lockdown has taken place in rural area of Penang Island and Kedah. At this stage, frequent accesses of the system are required and transient simulation is performed to determine compressor speed requirement. Re-adjustment of the gas flow by limiting flow to all the nodes at prelim input is carried out in the event that major supply and demand mix number deviates further. At this moment, uncertain

total gas demand is observed due to uncertain electricity requirement and industrial reaction towards full economic lockdown.

Actual pipeline pressure started to reduce after imposing 30% gas supply cutback at entry points on 19th March 2020, based on demand reduction response to ensure pipeline integrity remain intact. Piped gas entry point is limited based on technical limit and to allow processing plant to safely shutdown in case of high inventory storage in the pipeline system. At this stage, all supply data are captured and analysis is performed on historical data of low demand scenario. The simulated pressure of S1, S2 and S3 sustained in constant reducing trend returns to follow normal operating pressure guideline by 21st March 2020 within 30 -65 barg pressure limit. By having this input, transporter may continuously monitor system performance without exposure of abnormalities and significantly reduce high gas pressure and flow fluctuations in the system because of demand uncertainty. Further analysis of the trend revealed that several industries have applied the government permit to roll out intermediate preparations and inventory management. In this sense, electricity usage and gas requirement still at tolerable range. As a result, simulated pressure starts to alleviate and equalize at both S2 and S3 node due to balance gas demand distribution. In general, prediction of simulated pressure gives appropriate insight for pipeline operator to react on operational changes for faster decision making.

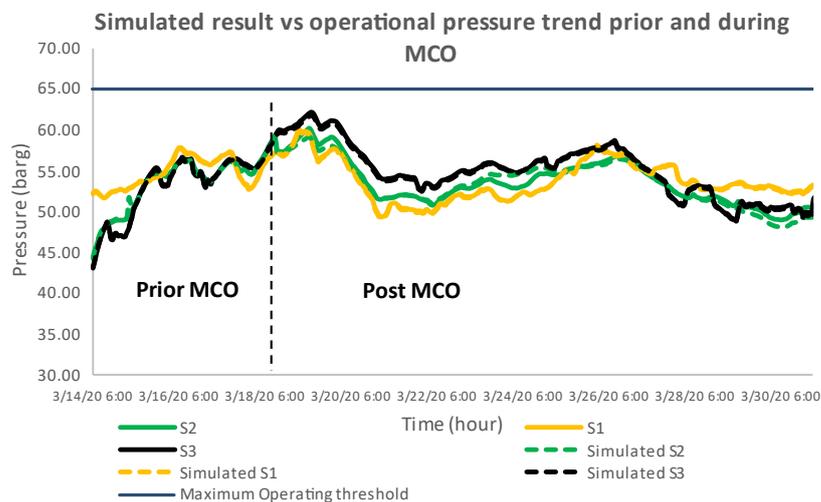


Fig. 11. Simulated vs. operational pressure result from period of 14-30 March 2020.

4.2. Simulation profile after MCO (economic lockdown) declaration

Post announcement of total economic lock down period, only essential businesses can operate with minimum manning. This category of essential businesses are Foods, Water, Energy, Communications and Internet, Security and Defense, Communications and Internet, Solid waste, Public cleansing management and Sewerage, Healthcare and medical, Banking and finance, E-commerce, and Logistics [56, 57]. On the first week after MCO declaration, actual gas demand is stable as per allocation number due to full economic lockdown and implementation

of working from home. As a result, simulated gas pressure for S1, S2 and S3 remain stable from 24th March 2020 until 28th March 2020. Simulated and operational pressure trends accordingly and able to implement shipper supply demand planning. Fortunately, more industries can operate following stringent guideline provided by government and increase gas demand respectively. On the next day, the gas demand starts to correspond with new working environment, enabling more gas to be supplied due to increase in electricity demand.

Based on the above case study, overall percentage of errors for S1 (0.29%), S2 (0.31%) and S3 (0.34%) is compared to operational pressure data. Total average of the error is 0.31%, slightly higher compared to abnormal case for pressure output 0.25% due to data accuracy and simulation assumptions used in the model. Highest simulated pressure is 61.87 barg at point S3 during 1st day of MCO declaration. The pipeline studio is able to simulate reasonable pressure outlook below than operational pressure limit at 65 barg. Hence, overall transmission network is within operational safety limit to operate during high pressure scenario.

In relation to this, optimal solutions to fine tune sustainable pressure are essential for pipeline operator to avoid any unwanted events, such as inventory overpressure situation. More importantly, this study resolves and achieves strategic objective of analysing gas demand uncertainty through MCO case study and solving high pressure fluctuation by providing a set of pressure forecast which reflecting a true planning and scheduling of gas pipeline system at Peninsular Malaysia. By having this opportunity, planner is able to increase the allocation of each exit point through pipeline simulator respectively. Hence, compressor stations can start to slowly ramp up as the pressure and pipeline inventory currently in reducing trend.

5. Conclusion

An analysis has been made of the uncertain gas demand scenarios by utilizing pipeline studio as a simulation tool. Transient model considers network pipeline configurations, network constraint, assumptions and modelling it via transient simulator. We analysed 30.21% gas demand reduction due to economic lockdown MCO, which caused high gas pipeline pressure. Highest recorded simulated pressure 61.87 barg, which is lower than maximum operational limit 65 barg. Hence, determining effects of gas pressure fluctuations and gas demand uncertainty into scenario planning is a very promising direction for research in view of uniqueness of Peninsular Malaysia electricity demand pattern. The future work can consider integrated simulation work for electricity and gas profile.

Nomenclatures

A	Approximate correlations for pseudo-critical pressure and temperature based on gas gravity. Can be found on Tarek Ahmed: Equations of State and PVT Analysis, 2006
B_o	Volume factor for gas formation
C_o	Gas Isothermal compressibility coefficient
D	Initial diameter, m
D_f	Diameter of pipeline at flowing condition, m
D_o	Heat capacity coefficient

E	Potential energy term, Pa ² , $E= 0.06843 d(H-H_1)(P_{avg}^2 / T_{avg} Z_{avg})$ [49]
E_o	Friction factor coefficient
f	Darcy friction coefficient
G	Gas relative density
h_2, h_1	Delta of high, length of the pipeline, m
K	K-factor, pulses/ft ³
L	Pipeline length, m
P	Pressure, Pa
p	Molar density, mol/m ³
P_c	Pressure at the critical point, refer to [55]
P_m, P_n	Legendre Polynomials of degree 0-5
P_r	Reduced pressure, refer to [55], barg
P_{st}	Pressure at standard condition, barg
Q_{st}	Volumetric flow rate at standard condition, m ³ /s
R	Gas constant, 8.314 kJ/(kmol.K)
Re	Reynolds number
T_c	Absolute temperature at the critical point, refer to [55]
T_r	Reduced temperature, refer to [55], °C
T_{st}	Temperature at standard condition, °C
Z	Compressibility factor of gas at standard condition
Z_{avg}	Compressibility factor of gas
Greek Symbols	
α	constant with respect to pressure in Peng-Robinson EOS
ε	Wall roughness, m
ρ	Gas density, kg/m ³
ω	Acentric factor
Abbreviations	
BWRS	Benedict-Webb-Rubin Equation of State
EC	Energy Commission
GDP	Gross Domestic Product
GSO	Grid System Operator
LNG	Liquified Natural Gas
MCO	Movement Control Order
MMscfd	Millions Standard Cubic Feet per Day
RE	Renewable Energy
SB	Single Buyer
SCADA	Supervisory Control, and Data Acquisition
WHO	World Health Organization

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Appendix A

Simulation used in this study

A. 1. Introduction

In this initial work, we have assessed gas flow equation, equation of state, demand behavior and impact of fluctuating pressure caused by customer offtake. We start with model development of pipeline network according to its design. The first step is a foundation part of compiling a set of supply and demand data on hourly basis and allocated it into respective exit points by utilising a spreadsheet file. Next, centrifugal compressors are identified along with technical inputs, inclusive of pipeline length, type, elevations, and internal diameter for the main line and lateral or branch line, respectively under data input. Once completed, the steps proceed with valve configurations based each pipeline sizing along with gas composition input for each gas supply to enable gas quality temperature tracking for the whole network system.

After completing model set up, customized supply demand forecast data is inserted into the model and run on timed steady state mode. AGA and BWRS is applied as equation of state, and gas flow equation or friction factor will correlate into model formulation as per sensitivity analysis. Next, the user run steady state to validate the result network. Each the step requires to run system adequacy check to ensure network model is consistent with actual site condition. If the result is found to be converged, proceed with transient simulation part. Otherwise, steady state input is applied and fix the error. Upon completion, the result will be extracted in illustrated in plot trend, hence can be proceeded with analysis for each identified location by gas pipeline operator which will be outlined in Chapter 3. The simulation model flow chart is shown in Fig. A-1.

Some considerations and assumptions are:

- Time stamp for the transient simulation by hourly basis.
- Fluid temperature is taken as 30 °C
- Maximum operating pressure is taken as 65 barg
- Minimum operating pressure is taken as 30 barg.

A. 2. Details of equation of state used in this paper

Below are details of equation input.

BWRS Equation details [55]

$$\frac{A_0\rho}{RT_c} = 1.28438 - 0.920731\omega \quad (7)$$

$$B_0\rho = 0.443690 + 0.115449\omega \quad (8)$$

$$\frac{D_0\rho}{RT_c} = 0.0307452 + 0.179433\omega \quad (9)$$

$$\frac{C_0\rho}{RT_c} = 0.356306 + 1.70871\omega \quad (10)$$

$$\frac{E_0\rho}{RT_c} = 0.006450 - 0.022143\omega \exp(-3.8\omega) \quad (11)$$

$$\frac{b\rho^2}{RT_c} = 0.528629 + 0.349261\omega \quad (12)$$

$$\frac{a\rho^2}{RT_c} = 0.484011 + 0.75413\omega \quad (13)$$

$$\frac{d\rho^2}{RT^2} = 0.0732828 + 0.463492\omega \quad (14)$$

$$\frac{c\rho^2}{RT^3} = 0.504087 + 1.32245\omega \quad (15)$$

$$\alpha_0\rho^3 = 0.0705233 - 0.044448\omega \quad (16)$$

$$\lambda\rho^2 = 0.544979 - 0.270896\omega \quad (17)$$

SAREM equation of state [29] and [55]

$$Z = \sum_{m=0}^5 A_m P_m \left(\frac{2P_r - 15}{14.8} \right) P_n \left(\frac{2T - 4}{1.9} \right)$$

$$P_n = \frac{Z}{\left(\frac{2P_r - 15}{14.8} \right) \left(\frac{2T - 4}{1.9} \right) x (A_0 P_0 + A_1 P_1 + A_2 P_2 + A_3 P_3 + A_4 P_4 + A_5)}$$

whereby

Table A-1. Sarem equation detail.

No.	Approximate correlations for pseudo-critical for T and P	Pseudo-critical pressure (MPa)
1	$A_0=0$	$P_0=20.28$
2	$A_1=0.57719$	$P_1=20.78$
3	$A_2=0.9882$	$P_2=24.23$
4	$A_3=0.89705$	$P_3=27.68$
5	$A_4=0.9182$	$P_4=31.13$
6	$A_5=0.75677$	$P_5=34.58$

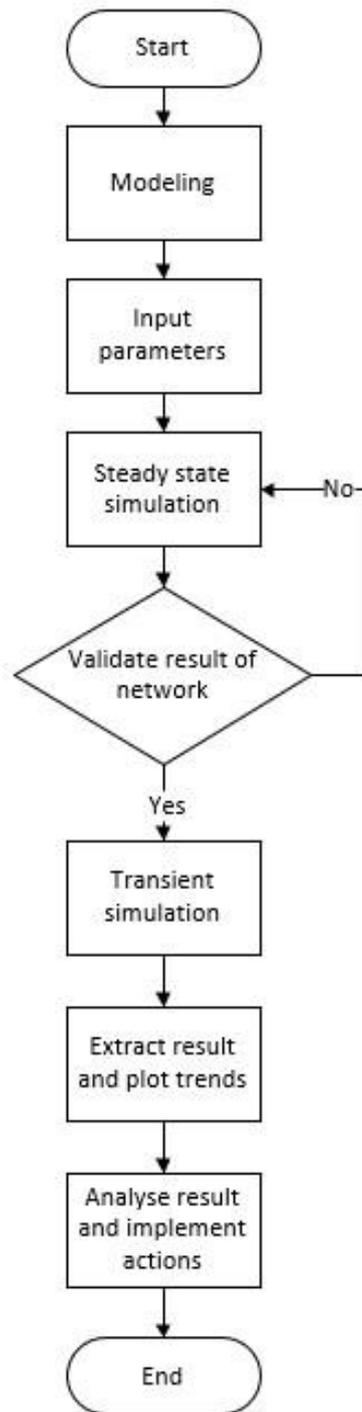


Fig A-1. Simulation model flow chart.