TECHNICAL AND ECONOMIC ANALYSIS OF HYDRAULIC PUMPS IN DELIQUIFYING GAS WELLS

by

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DISSERTATION

Submitted to the Geosciences and Petroleum Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved by,

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Universiti Teknologi PETRONAS

TRONOH, PERAK

May 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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LYE YAN CHING

ABSTRACT

This paper presents the concepts of deliquifying gas wells using one of the methods to unload liquid gas wells: hydraulic pumping. Liquid loading is the inability of produced gas to remove liquids produced together from the wellbore. This is a well-known phenomenon in mature gas wells. As production depletes, the reservoir loses energy and therefore allowing liquids to accumulate at bottomhole. The backpressure created from liquid loading can reduce gas production and with time, might even kill the well. Deliquification or liquid unloading - the process of removing associated liquids from the produced gas is severely critical for mature gas wells.

The author subsequently explores the theory and working principles of hydraulic piston pumps and hydraulic jet pumps. Both types of pumps have different specifications that can be suited for different cases. In order to further contrast the specifications, the author will compare hydraulic pumping with gas-lift system, one of the pioneer methods used in the industry. As to validate the system feasibility, the author generated a mechanism for technical and economic analysis, to provide system requirement from production projection to users. System requirement is crucial as to assess viability of system to be installed and operated. The economics involved in the process will be analysed through computer coding generated. Economic analysis is vital in the selection of deliquification method; operational benefits must be in balance with the economic value so that the costing is economically viable. Expansive research and studies have been made on the theories of the pumps.

This progress report carries the objectives to update the advancement of project since Progress report in FYP II. Since that, the author refined and improvised the mechanism through Microsoft Excel Spreadsheet. The author has developed a set of computer coding to ease technical and economic analysis when determining system compatibility. Sensitivity studies were conducted to analyse the parameters' relationships.

ACKNOWLEDGEMENTS

Success is a journey, not a destination. First of all, I would like to express gratitude to the Almighty for blessing me with the strength to endure the challenging Final Year Project and for offering me chances to learn and gain great experience. It has been a very eye-opening, humbling and enriching experience.

Secondly, I would like to thank my university, Universiti Teknologi PETRONAS (UTP), my awesome Supervisor, Mr. Mohd Amin Shoushtari for his guidance throughout the project. I would love to thank my fellow coursemates as well for their constant support, patience and willingness to share their knowledge.

Credits to UTP for offering us the students a chance to explore our potential and express our creativity and innovation on this subject. In general, this project offers the students a chance to mature in the field of study as well as getting them prepared to the demands of the current Oil and Gas Industry that requires personnel to be inquisitive and equipped with research based knowledge.

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CHAPTER 1
INTRODUCTION

1.1 Background

Hydrocarbon production can be divided into different categories, namely the gases, fuels, waxes and all. This project puts focus on gas production and one of the major problem faced in gas production, especially for mature gas wells. James F. Lea, Henry V. Nickens, Mike R. Wells [7] explained the concept of liquid loading in gas wells and the problems caused by liquid loading. Liquid loading can lead to erratic, slugging flow, decreased production and will eventually kills the well if the liquids are not continuously removed. The problems of liquid loading in gas wells is due to hydrostatic weight that exerts back pressure on the formation, choking the flow and consequently stops the production.

Since liquid loading can cause such severity in depleting gas production, liquid unloading techniques are relatively important. A.V. Bondurant, B.D. Dotson, P.O. Oyewole [1] defined deliquification as the process of removing associated liquids, which could be water, oils or condensates, from wellbore and reservoir to the surface. James F. Lea et al. [7] listed the possible sources of produced liquids as below:

- Water coning
- Aquifer water
- Water produced from another zone
- Free formation water
- Water of condensation
- Hydrocarbon condensates

Deliquifying techniques were vastly developed since the history of gas well drilling started. For this paper, the author scopes down to hydraulic pumping and gas lift, few techniques that have been practiced since 1800s. The reason author picked these three is because the application theory and principle are more or less similar and hence were widely misused in the production industry. Hydraulic pumping was used to produce oil wells back then. It is now used as a form of artificial lift through reciprocating downhole piston pump or jet pump. However, as compared to gas lift, which was first used in 1846, hydraulic pumping which was first used in 1930 is a relatively new method of artificial lift [7]. Gas lift has been so vastly in use since the interventions involved are relatively less expensive, reliable, closely matches the well natural production characteristics [12].

This project involves the study and comparisons of hydraulic pumping working principle, for hydraulic piston and hydraulic jet pumps. On top of that, thorough comparisons between hydraulic pumping and gas lift are made. The author developed a selector to aid in selection of deliquification method. After selecting a method out of the 3 mentioned above, technical analysis will be carried out to verify viability of system. Every operation involves economic summary analysis. In this project, economics included in different types of deliquification operations will be carefully analysed. The summary of economic analysis will later be used as comparisons between both types of pump and gas lift operations. The economic values have to be at par with the operational benefits.

1.2 Problem Statement

Liquid loading leads to a lot of problems to production of gas wells. Production rate will decrease, and as the well loses energy with time, the liquid accumulated at the bottom of the hole might cease the production.

i. In recent years, hydraulic pumping has proven its effectiveness in gas wells deliquification worldwide. There is a need to compare this method with the pioneer liquid unloading technique, gas lift. The comparison is extremely crucial in selecting liquid unloading method suited for different situations.

ii. The difference of operating principles and conditions between the two types of hydraulic pump, the hydraulic piston pump and hydraulic jet pump should be further studied and contrasted to best fit various conditions.

iii. The technical and economic feasibility of hydraulic pumping and gas lift as gas well deliquification method must be analysed in order to balance the operational benefits and profitability. Moreover, comparisons between both types of pumps with the gas-lift system in terms of economics are needed as well.

1.3 Objective

The objectives of this project are:

i. To analyse the working principles of hydraulic pumping with the versatile gas lift for liquid unloading.

ii. To investigate the difference between hydraulic piston pump and hydraulic jet pump to efficiently solve liquid loading problem in various conditions.

iii. To analyse the technical and economic feasibility of hydraulic pumping and gas lift to keep the operational benefits and profitability in balance. On top of that, difference of both types of pumps in terms of economics will be evaluated.

1.4 Scope of Study

For this project, the focus is placed on gas well deliquification using hydraulic pumping in vertical well and analysis of economics involved. The scope of study includes:

i. Conducting research on the theory and definition of terms related to the study.

ii. Expansive study on working principles for various gas well deliquifying methods through technical articles, online journals, books and other sources.

iii. Exploration of numerous programmes and software to generate a set of code for gas well deliquification technical and economic analysis.

1.5 The Relevancy of the Project

Researches and studies conducted have shown the increasing numbers of wells affected by liquid loading problem. This is a phenomenon faced by gas wells operator all around the globe. Liquid unloading or gas well deliquification is hence, extremely vital in this industry.

1.6 Feasibility of the Project within the Scope and Time Frame

Since Final Year Project will go on for two semesters, the first semesters will be used to conduct preliminary research and studies. Technical reports, online journals, case studies will be included as sources for the preliminary study phase. Plans will be made and summarised in Gantt chart as to keep the time and work on track. The time frame of 8 months will be fully utilised to achieve the objectives tabulated earlier. In short, this project is feasible within the scope and time frame if project activities go with time as planned.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Gas Well Deliquification

W. Hearn [5] defined liquid loading of gas well as the inability of the produced gas to remove the liquids from the wellbore. An increasing number of gas wells worldwide produce at rates below their maximum potential due to liquid loading, which occurs when the gas velocity in the well falls below a critical value, at which point the liquid that was previously carried upward by the gas begins to fall back. The liquid accumulated downhole, where it increases the hydrostatic back pressure on the reservoir, destabilizes the multiphase flow in the well, decreases gas production rate and in severe cases, can kill the wells [24]. Liquid loading happens when the velocity of the produced gas decreases to a velocity until liquids were unable to be lifted. James F. Lea [6] wrote that critical velocity is the minimum gas velocity in the production tubing required to move liquid droplets upward. As gas production decreases, liquid loading is more likely to occur. In normal cases where gas flows naturally and steadily, the gas has velocity high enough to carry any liquids to surface. Liquids are finely dispersed into the gas stream resulting in a mist flow pattern. Consequently, a very low volume of remaining liquid is present in the production tubing and the low backpressure, caused by gravity effect will act on the flow stream. This phenomenon will then cause resulting flow patterns to be annular or slug flow. Production of gas will then be affected [26].

The greatest engineering challenge to the operation is to unload liquids entering the wellbore. Connate fluids, condensates, pressure and temperature loss over time can create more liquids, which then produces backpressure and risking the production rate [7]. Eventually, the backpressure will increase until the well is killed by the water column overbalance [8]. Primary cause of liquid loading is gradual decline in formation gas-liquid ratio (GLR) below critical or unloading gas rate for applicable size tubing [11]. This backpressure or bottomhole pressure has the following components:

i. Hydrostatic pressure of the producing fluid column.
ii. Friction pressure caused by fluid movement through the tubing, wellhead and surface equipment.
iii. Kinetic or potential losses due to diameter restrictions, pipe bends or elevation changes.

A.V. Bondurant [1] also commented that the challenge of dealing with unconventional gas resources is that the ultimate recovery is dependent on economic removal of liquids accumulation, generally termed “deliquification”. Low rate gas wells almost always cease production due to liquid accumulation in the wellbore.

As the reservoir pressure depletes production rate, the gas flow velocity reduces below a critical velocity required for gas to move liquid droplets up to surface. Liquid then begins to accumulate at bottomhole near wellbore region. The bottomhole flowing pressure then increases due to an increase in liquid holdup in the tubing. The relative permeability of gas and gas mobility in near wellbore region will also be impaired since water saturation increased. This acts like skin damage to the reservoir, known as “liquid block” [25]. R.D. Haydel presented the primary cause of liquid loading in gas wells in his paper. It is the gradual decline in the formation gas-liquid ratio (GLR) below the critical or unloading gas rate for the applicable size tubing [11]. As time goes, the perforated intervals in wells will be covered by wellbore fluids and the wells will be killed. He also presented the indicator of liquid loading presence in the form of graph. The common signs of liquid loading include tubing and casing pressure differential, sudden pressure spikes, liquid slugging, fluctuating gas production, production drops below decline curve and in the most serious case, liquid production stops altogether.

J. F. Lea and H.V. Nickens [6] suggested few actions to be taken to reduce liquid loading as follows:

- Flow the well at high velocity to stay in mist flow, smaller tubing is used and lower wellhead pressure can be created.
- Pump or gas lifts the liquids out of the well.
- Foam the liquids, or inject water into an underlying disposal zone.
- Prevent liquid formation or production into the well.

Earlier this year (2013), A.D. Suhendar and his team from VICO Indonesia summarized that there are three most common ways to recognize liquid loading [26]:

i. **Observing well's production symptoms (fluid rate & pressure).**

In the Figure 1 below, the sharp and inexplicable drop in the well's production is a strong indication of liquid loading. On steady state flow conditions, a gas well decline curve should be smooth and gradual from reservoir standpoint. The sharp drop in decline curve and possible erratic surface pressures are indicators of production problem, especially liquid loading in tubing.

If available, pressure gradient in tubing is one of the best indicators; a normal gas well would show a smooth gas gradient.

ii. **Calculating critical velocity and monitor from there**

The aforementioned critical velocity has been defined in the industry as a critical parameter of a well's flow. If the flow rate is below the critical rate, liquid loading will takes place. Turner defined a formula as to calculate critical velocity for gas wells with wellhead pressure greater than 1000psi, as shown below:

$$V_t = \frac{2.04\ \sigma^{\frac{1}{4}}(\rho_L - \rho_G)^{\frac{1}{4}}}{\rho_G^{\frac{1}{2}}} \quad (1)$$

Where σ = Surface tension in dynes/cm ; ρ_L & ρ_G = density in lbm/ft^3.

Coleman predicts that critical rate is 20% lower than Turner's rate for gas wells with wellhead pressure less than 1000psi [26].

iii. Doing standard nodal analysis

Nodal analysis can analyse the effects of several parameters in the inflow and outflow performance curve for the ability of gas to produce reservoir liquids. Hence it can be used to evaluate the flow conditions and the deliquification options.

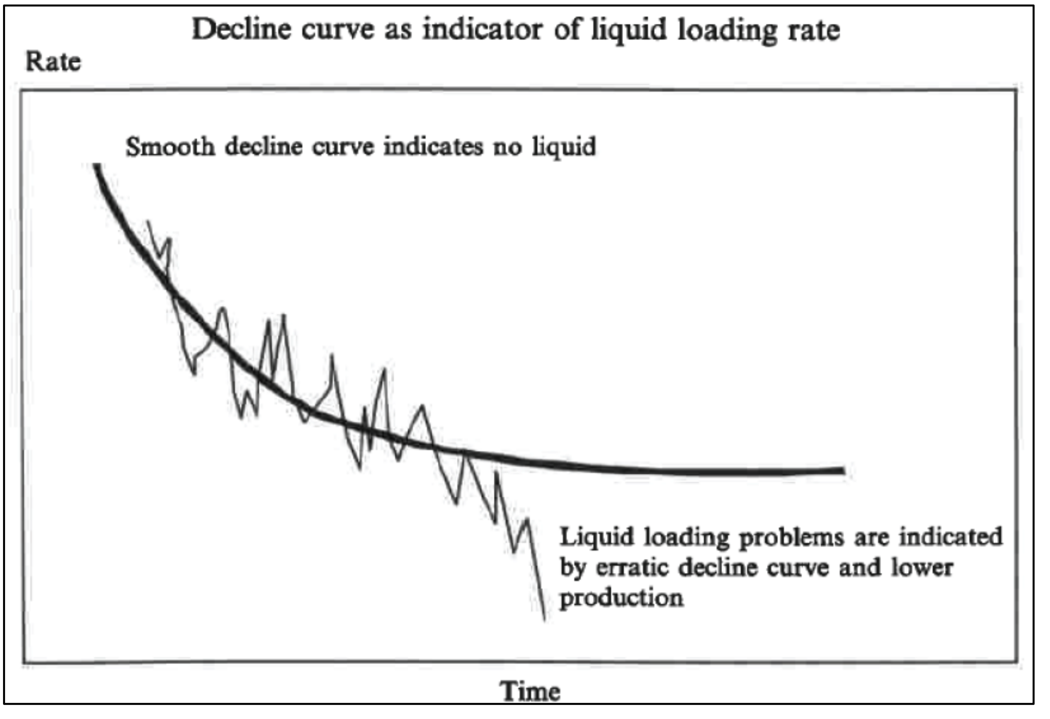


Figure 1: Decline curve showing onset of liquid loading [11].

Choosing the optimum solution for a specific occurrence of loading in the field is a very challenging task that requires an integrated, multi-disciplinary approach to deliver the highest possible value for the asset [24]. There are many factors to be considered when screening for liquid unloading options:

- Field Location
- Well Characteristics
- Fluid Properties
- Power and Service Availability
- Surface Facilities
- Reservoir Characteristics
- Operating Constraints (System)

- Cost
- Production Projection and Estimation

Weatherford International® has an unloading selector, which is a logical artificial lift application selection process for gas well deliquification. This works by assigning a high or low value to each of only four readily available surface-gathered data points – liquid flow rate, flowing tubing pressure, water cut percentage and gas liquid ratio. After matching the data values with the variables, the outer most ring colour will then direct to four portions of purple (Positive-Displacement Lift), yellow (Plunger Lift), blue (Fluid Power Lift) or orange (Foam Lift). Once the lift selection has been identified, the four quadrants following different colours will provide further analysis of that lift selection [10].

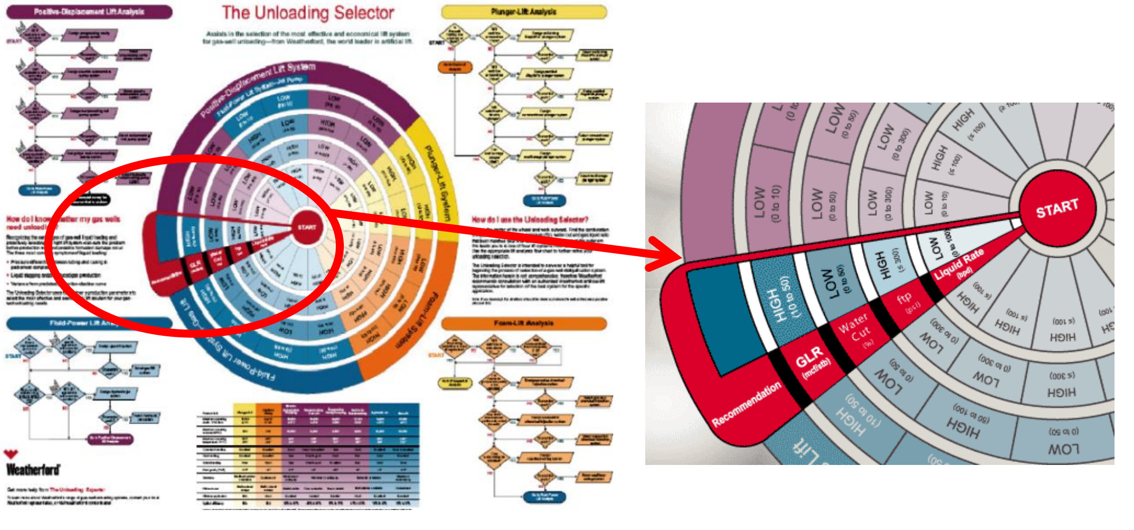


Figure 2: Weatherford International® Unloading Selector for Gas Well Deliquification [10].

Currently there are a few published papers which proposed several types of decision matric to screen the possible remedial options available to the operator; some are based on an assessment algorithm used in conjunction with a decision tree [28]. However, depending merely on technical analysis is not very useful for selecting best options for long-term deliquification of the well. Because the well productive characteristics vary so widely, the current and future productive potential of the well are not quantitatively considered in these methods. Hence, economic analysis is utmost crucial [27].

2.2 Hydraulic Pumping System

J. F. Lea [6] described hydraulic pumping as the hydraulically powered downhole pumps, powered by a stream of high-pressure water or power fluid. The major advantage of hydraulic pumping is that it can operate over a wide range of well conditions, such as setting depths of as much as 18,000 feet and production rates of as much as 50,000 barrels per day. Moreover, no rig is needed to retrieve pumps. Hydraulic pumping is a very flexible system in adjusting to changing production rates. Hydraulic pumps are generally used for [3]:

- ✓ Permanent production or well clean up
- ✓ Well productivity evaluation
- ✓ ***Unloading gas wells***
- ✓ Drill stem testing
- ✓ Wireline retrievable systems

Hydraulic pumping is often preferred when the operation requires a more flexible system which is adjustable to changing production rates. Hydraulic pumping system can also produce in higher rates from greater depths as compared to methods like rod pumps, ESP or gas lift. Chemicals can be added into the power fluid to control corrosion, paraffin and etcetera.

There are two types of hydraulic pumps, the characteristics are as follows:

i. Hydraulic Piston Pumps
   - Suitable for oil exploration of deep wells with high wax content.
   - Big pump setting depth, large displacement.
   - Simple structure; Rod string not required.
   - High efficiency, high reliability. High resistance to high temperature and corrosives. Low tolerance to solids in production fluids.
   - High complexity in manufacturing of piston pumps. High initial capital cost.
   - The reciprocating pump piston is driven by hydraulic “engine” section which then converts continuous flow of power fluid into reciprocating motion [9].

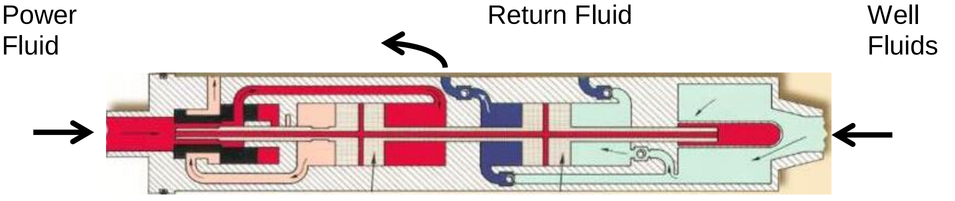


Figure 3: Illustration of hydraulic piston pump [9].

ii. Hydraulic Jet Pumps

- Suitable for wells with high gas-liquid ratios (GLR).
- Can operate reliably in deviated wells.
- Long lifespan, simple structure, no moving parts.
- High efficiency, high reliability. High resistance to high temperature, solids and corrosives.
- Low repair and maintenance costs.
- Requires specific bottomhole assembly (BHA).
- Requires minimum flowing bottomhole pressure to "pump-off" a well, to avoid power fluid cavitation.
- Operate based on the venture nozzle principles whereby kinetic energy of high pressure low velocity fluid is converted to low pressure/ high velocity as fluid flow pass nozzle [9].

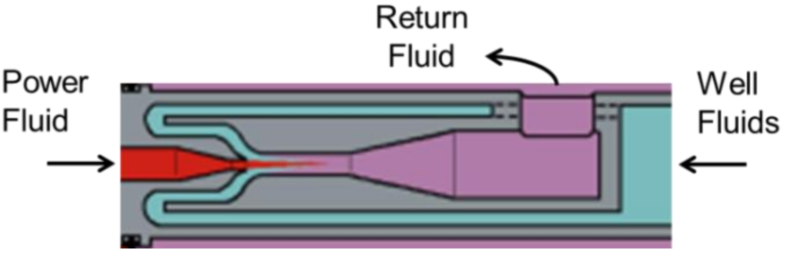


Figure 4: Illustration of hydraulic jet pump [9].

R. R. Algrage [14] addressed the efficiency of hydraulic jet pump system in his recent paper. During 30 years of operations, many types of artificial lift trial have been performed, such as electric submersible pump (ESP), rod pump (HPU) and hydraulic jet pump (HJP). Given that TBL sandstone formation has solid problem, rig mobilization and operations are very costly, high deviated well construction, so

HJP became the obvious choice. Currently 43 active oil wells in Sembakung are producing with the aid of HJP as artificial lift, contributing 2,200 BOPD productions in year 2000-2010. The HJP bring additional advantages apart from the fundamental benefits like high solid resistance and high tolerance to deviated wells.

- ✓ Rigless installation of HJP assembly
- ✓ Easy to service and maintain
- ✓ Minimum well downtime

As compared to gas lift, downhole pumps are normally more effective, since it will be physically located below the bottom perforation and liquid will be mechanically removed with outside energy source [15]. J.A. Babbit and F. K. Kpodo presented their innovations in jet pump design and applications in field. The field data and net cash flow were then used in the research [21] [22].

2.3 Gas Lift System

Gas lift is a popular artificial-lift method in which gas is injected into the production tubing to reduce the hydrostatic pressure of the fluid column. The resulting reduction in bottomhole pressure allows the reservoir liquids to enter the wellbore at a higher flow rate [12]. The injection gas is typically conveyed down the tubing-casing annulus and enters the production train through a series of gas-lift valves. The gas-lift valve position, operating pressures and gas injection rate are determined by specific well conditions.

There are typically 2 types of gas-lift system:

i. Continuous flow gas lift
ii. Intermittent gas lift

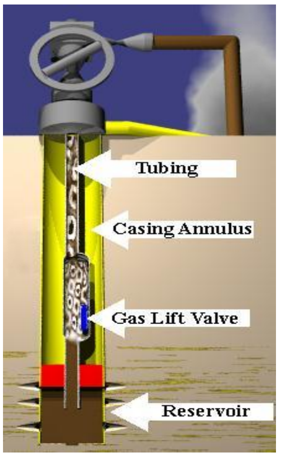


Figure 5: Configuration of a Gas-Lift System [12].

Table 1: Specifications of different types of Gas-Lift System.

CONDITION	CONTINUOUS FLOW	INTERMITTENT FLOW
Production Rate (bbl/day)	100 – 75,000	Up to 500
Static BHP (psi)	> 0.3 psi/ft	< 0.3 psi/ft
Flowing BHP (psi)	> 0.08 psi/ft	150 psi and higher
Injection gas (scf/bbl)	50 – 250 per 1000 ft of lift	250 – 300 per 1000 ft of lift
Injection Pressure (psi)	> 100 psi per 1000 ft of lift	< 100 psi per 1000 ft of lift
Gas injection rate	Larger volumes	Smaller volumes

2.4 Economic Analysis

R.V. Dort [4] proved in his study that approximately 90% of 775,000 active gas wells globally suffer from liquid loading. Hence, there is increasing demand for reliable and effective deliquification solutions. He also mentioned that the potential economic deliquification benefits are significant. This is because most of the wells are mature gas wells and were not originally completed with the purpose of deliquification in mind. The remaining lifespan of wells has to be taken into consideration before investing significant amount of money as there is increased risk of not recouping the original investment.

Gas well deliquification is an operation which requires high amount of money as investment. Hence, the income by average gas net production per well has to be calculated. M. Amani [2] made the remark that in order to evaluate the economics of a particular artificial lift system, costs such as installation, power, repair, maintenance and operating labour costs have to be included in analysis. The selection of artificial lift systems depends on many factors other than costs (As shown in Figure 2: Weatherford International® Unloading Selector for Gas Well Deliquification [10]). He also presented a case study where he concluded capital cost of the gas lift system is much higher than hydraulic gas pump, in the case of University 18-30 Gas Unit 1 in Texas, United States of America. That is due to the cost of casing installation involved in gas lift system. In a hydraulic pump system, there is no need for new casing string installation

M. Amani [3] tabulated a list of major equipment and costs estimated to illustrate the economic viability of the hydraulic pumping system. The costs vary substantially by depth and desired production rate. In Amani's paper [3], the economic analysis was done using case study where the hydraulic pump can pump 400 barrels per day from 8000 feet. Approximately $130,000 was needed for the cost of major equipment.

Table 2: Costing summary in M. Amani's case study [3].

Table 2– List of major equipment for a Hydraulic Gas Pump. Lift Depth 8000', 400 BLPD

Subsurface Valve Assembly	$ 8,300
Hydraulic Control Line & Fluid (7618',1/4",$2/ft)	15,236
Surface Controller	8,000
Coiled Tubing (7,618',1",$1/ft)	7,618
Pressure Vessel (150',7" csg, Drilled & cemented)	6,000
Surface Valves	2,500
Compressor (100 - 4500 psig, 400 scf/min 145 BHP Electric Motor)	81,895
Total	$129,549

D.B. Foo [13] documented case studies in Western Sedimentary Basin at various depths and producing conditions. The results include production increases of 25% with reduced operating costs.

The figure below shows the summary of economic analysis made on a field in North America after hydraulic jet lift system was implemented to deliquify gas wells [3]. M. Amani also mentioned that in order to save costs, several wells can be connected to one compressor station to power the pumps. The summary is presented as Cost-Benefit analysis based on net production.

In order to quantify the benefits of a pump compared to other methods, production scenario for the pump must be projected and gas recovery has to be calculated to economic limit. Generally, the capital cost of gas lift system is higher than hydraulic pumping. This is due to the installation of casing for gas lift operation, to provide protection from high pressure.

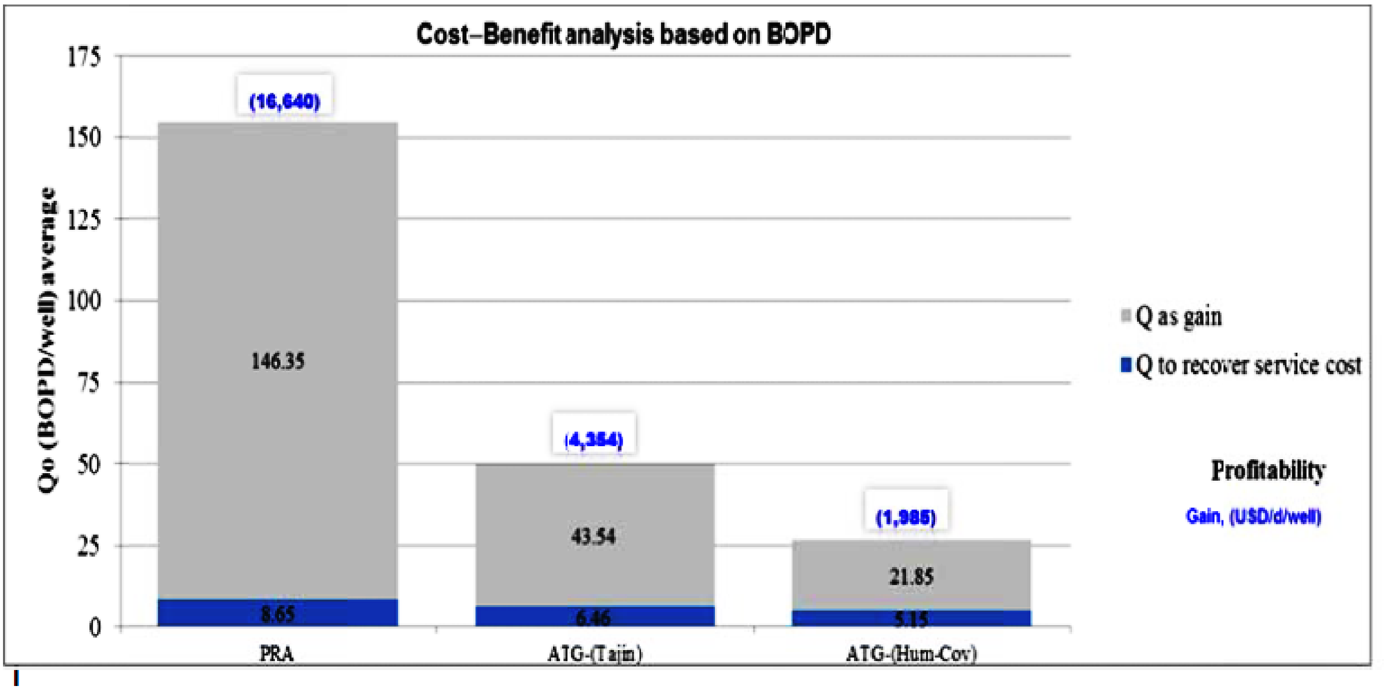


Figure 6: Cost-Benefit Analysis for hydraulic jet lift system application in AIATG and AIPRA assets [19].

In order to generate computer coding for economic analysis, inputs were gathered from various studies. P.R. Newendorp, K. E. Brown and H. D. Beggs listed the indicators to be taken into account when computing the economics of projects. For instance, Pay-out period, Net present value (NPV), Internal Rate of return (IRR), Profit-to-investment ratio, Time-value of money, Discounted profit-to-investment ratio (to today's value), Appreciation of equity, Percentage gain and investment, Analysis of rate acceleration projects and etcetera [16] [17] [18].

CHAPTER 3
METHODOLOGY AND PROJECT ACTIVITIES

This chapter comprises the methods author going to use in order to achieve objectives stated earlier. Through research, the author will be able to obtain all the information needed to proceed with the project. Project activities indicate agendas the author would need to go through. Gantt chart places time frame for the author to achieve key milestones in FYP I and FYP II.

This final year project consists of 2 major parts:

I. Comparative Analysis of Hydraulic Pumping and Gas-Lift System.
II. Mechanism for Technical and Economic Analysis of Deliquification Methods.

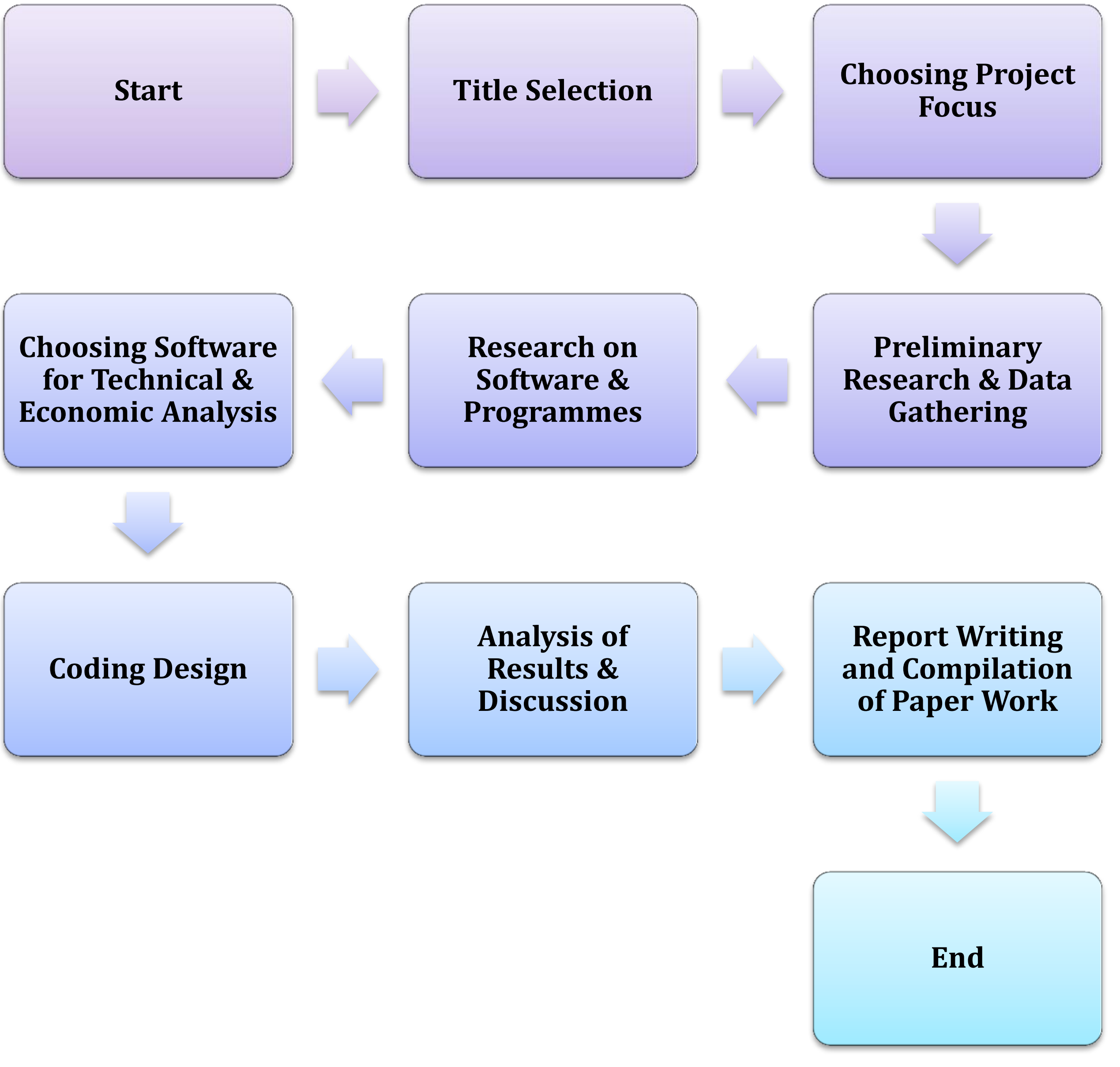
3.1 Research Methodology

This section consists of project analysis, which involves data and information gathering through online sources, technical papers published in SPE and Oil and Gas related websites, books and etcetera. Plenty of research is conducted to gain a good understanding on the subject such as critical velocity, liquid loading, gas well deliquification, gas lift, hydraulic pumping, hydraulic piston pumps and hydraulic jet pumps. Moreover, case studies related to the topic were carefully analysed so as to grasp the working principles of various liquid unloading methods and the economic factors involved. Furthermore, some articles on economic analysis were studied as well.

Numerous software and programmes were explored to find the one best fit to analyse economics involved in gas well deliquification using hydraulic pumping and gas lift.

Only after the understandings of all the subjects then the author would be able to identify the major problem and complete the project.

3.2 Project Activities



3.3 Key Milestones and Gantt Chart

Table 3: Gantt Chart and Key Milestones for Final Year Project I

Key Milestones	**Week**														
	1	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**
Selection of Title/ Topic	■	■						**MID SEMESTER BREAK**							
Preliminary Research Work		■	■	■	■	■									
Research Status : • Basic Understanding on Liquid Unloading Theory & Methods					■	■	■								
Submission of Extended Proposal							■								
Research Status : • Understand Working Principles of Hydraulic Pumping						■	■		■	■					
Proposal Defense									■	■					
Continuation of Project Works • Compare And Contrast Both Types Of Hydraulic Pumps											■	■	■		
Submission of Interim Draft Report														■	
Submission of Interim Report															■

Table 4: Gantt Chart and Key Milestones for Final Year Project II

Key Milestones	**Week**															
	1	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Continuation of Project Works • Draft Economic Analysis for Case Study • Draft s for Economic Analysis								**MID SEMESTER BREAK**								
Submission of Progress Report																
Continuation of Project Works • Finalize Analysis and Generate Coding																
Pre-SEDEX																
Submission of Draft Report																
Submission of Technical Paper																
Submission of Project Dissertation (Soft Bound)																
Oral Presentation (VIVA)																
Submission of Project Dissertation (Hard Bound)																

3.4 Technical Analysis Procedure

After conducting the necessary research, a spreadsheet was developed, comprising 3 parts:

I. Gas Well Deliquification Method Selector
II. Technical Analysis of Method Selected
III. Economic Analysis of Method Selected

On top of that, sensitivity analysis from technical and economic aspects will be conducted in order to show the relationships between the parameters involved.

For technical analysis, Kpodo, Babbit and Speer [21], [22], [23] defined a few parameters which can validate viability of an energy adding system, in the liquid unloading application. In this project's technical analysis, the author use minimum required hydraulic horsepower as a ruler, to determine system feasibility. This is achieved by comparing system required horsepower and the readily available horsepower onsite. In order to compute this minimum required hydraulic horsepower (HHP_{req}), several inputs are compulsory:

i. Power fluid rate – Capacity of pump
ii. System efficiency
iii. Required surface operating pressure (Wellhead Pressure)

Besides the HHP_{req}, the technical analysis will compute desired productivity index (J) and maximum flow rate, or absolute open flow (AOF). These are useful for users as to match with current production profile or the initial conditions. These 2 outputs are affected by:

i. Reservoir pressure
ii. Desired production rate
iii. Required producing pressure
iv. AOF will be affected by Desired productivity index (J)

Details will be analysed and discussed in the following chapter. Complete spreadsheet will be attached in Appendix section.

3.5 Economic Analysis Procedure

The second part of the analysis is to economically analyse the deliquification projects using gas lift and hydraulic pump. According to M. Amani, to quantify the benefits of a pump compared to gas lift, one must project a production scenario for the pump and calculate gas recovery to economic limit [2]. P.D. Newendorp and Campbell suggested that to obtain a good measure of value, suitable for comparing and ranking the profitability of investment opportunities, we should consider the following indicators:

1. Pay-out
2. **Net present value (NPV)**
3. **Internal Rate of return (IRR)**
4. Profit-to-investment ratio
5. Time-value of money
6. Discounted profit-to-investment ratio (to today's value)
7. Appreciation of equity
8. Percentage gain and investment
9. Analysis of rate acceleration projects

The first 3 factors are crucial and most widely used to rank desirability of projects [16]. Details will be analysed and discussed in the following chapter. Complete spreadsheet will be attached in Appendix section.

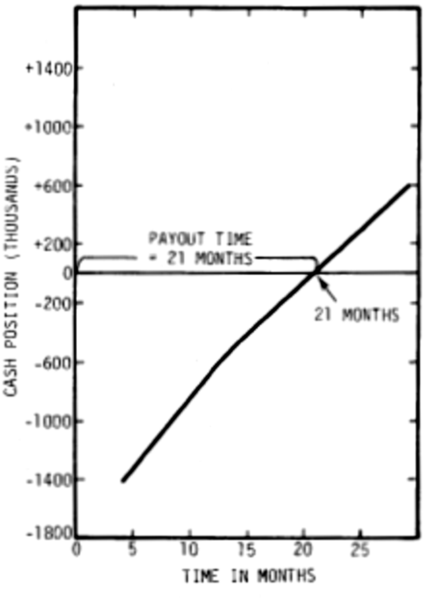


Figure 7: Cash position curve for Pay-out period by K. Brown [17].

CHAPTER 4
FINDINGS, RESULTS & DISCUSSION

4.1 Comparisons between Hydraulic Pumps

In general, hydraulic pumping systems convey energy to the bottom of the well by pressurized power fluid that flows down in the wellbore to a subsurface pump. These systems are very adaptable and have been used in shallow depths (1000 ft) to deeper wells (18000 ft), low rate wells with production in the tens of barrels per day to wells producing in excess of 20,000 bbl per day. Certain chemicals can be mixed in with the power fluid to help control corrosion, paraffin and emulsion problems. Hydraulic pumping systems are also suitable for deviated wells where conventional pumps such as the rod pump are not feasible. Some types of hydraulic pumps may be sensitive to solids, while jet pumps can pump solids volume fractions of more than 50%.The life-cycle cost of these systems is similar to other types of artificial lift when appropriately designed they are typically low maintenance, with jet pumps for instance having slightly higher operating costs with considerably lower purchase cost and virtually no repair cost.

- ### 4.1.1 Hydraulic Piston Pump

This type of pump is recognized for the flexibility and capability to operate in high-volume, high depth environments, this system provide extraordinary flexibility in installation and operation to meet a broad range of artificial-lift requirements. The general operating depths are 5,000 to 17,000 ft (1,524 to 5,182 m) with volumes from 50 to 25,000 BFPD. Due to complex machinery parts, hydraulic piston pump basically has lower solid tolerance. The specifications will be presented in Section 4.3.

- **4.1.2 Hydraulic Jet Pump**

Hydraulic jet pumps provide proven performance in almost limitless applications covering a wide range of depths, volumes and well conditions. With no moving parts, jet pumps provide greater reliability and serviceability, which is a real plus in remote locations. Its shorter length also provides easier passage through problematic boreholes. It has high volume capability, suitable for deviated wells, low maintenance costs. It normally performs better in higher GLR wells with amazing long run lives. Hydraulic jet pumps can be used even in high temperature 400◦F, by using high temperature elastomers for O-rings and seal rings. The specifications will be presented in Section 4.3.

- **4.1.3 Hydraulic Pump Operating Systems**

Open Power Fluid System (For both types of pumps)

- Allow gas to bypass the pump via casing-tubing annulus
- 2 downhole fluid conduits needed
    - Tubing contains the pressurized power fluid, directs it to the pump
    - Casing-tubing annulus returns both spent and produced fluid to surface
- Simple, more commonly-used
- Economically viable
- Power fluid and produced fluid intermingle
    - Additives in power fluid – extend life of the subsurface equipment.

    - Comingled power fluid can dilute highly-corrosive production fluids and reduce viscosity of heavy oils.
- This system allows circulation of heated liquids of dissolving agents – Remove waxy build-ups that may hinder or halt production.
- Drawback: all the gas must go through pump, piston pumps have a tendency to gas lock, throats of jet pump have tendency to be choked, inhibiting production.

Closed Power Fluid System (For hydraulic piston pumps only)

- An extra tubing is needed downhole - to bring the spent power fluid to surface
- Extra tubing on surface- carry spent power fluid to power fluid tank for recirculation and repressurization
- Less common as compared to OPF
- Smaller size of surface facilities
- Pump end is lubricated by power fluid; Engine piston designed to have +/- 10% leakage, causing power 10% power fluid to be lost into production. This must be fed back from production line.

4.2 Gas-Lift System

Gas is injected into the production tubing; reduce the hydrostatic pressure of the fluid column. Reduction in bottomhole pressure allows the reservoir liquids to enter the wellbore at a higher flow rate. The gas-lift valve position, operating pressures and gas injection rate are determined by specific well conditions. The specifications will be presented in Section 4.3.

4.3 Comparisons between Hydraulic Pumps and Gas-Lift System

Table 5: Comparisons of hydraulic pumps and gas-lift system.

Comparisons	Hydraulic Pump		Gas Lift
	Piston	Jet	
Maximum operating depth, TVD	17,000 ft 5,182 m	15,000 ft 4,572 m	18,000 ft 4,878 m
Minimum operating depth, TVD	5,000 ft 1,524 m	5,000 ft 1,524 m	8,000 ft 2,438 m
Maximum operating volume (BFPD)	8,000	20,000	50,000
Maximum operating temperature	550 °F 288 °C	550 °F 288 °C	450 °F 232 °C
Corrosion Handling	Good	**Excellent**	Good to Excellent
Gas Handling	Fair	Good	Excellent
Solids Handling	Fair	Good	Good
Fluid Gravity (°API)	>8 (Extra heavy crude)	>8 (Extra heavy crude)	>15 (Heavy crude)
Servicing	Hydraulic of wireline		Wireline or workover rig
Prime Mover	Multicylinder or electric		Compressor
Offshore Application	Good	Excellent	Excellent
System efficiency	45 – 55% -less mechanical work, less problem	10 – 30% -more sophisticated mechanical components	10 – 30%

4.4 Construction and Development of Spreadsheet – Technical Aspect

4.4.1 Gas Well Deliquification Method Selector

This is Step 1 of the spreadsheet developed by author. Weatherford International developed its Unloading Selector ® which included a lot of unloading methods. In this project, the author modified and adjusted the selector to better suit the current conditions since the author includes only the hydraulic piston pump, hydraulic jet pump and gas lift system into account. The author presents the selector in flow-chart as shown below, where users are required to consider a few factors.

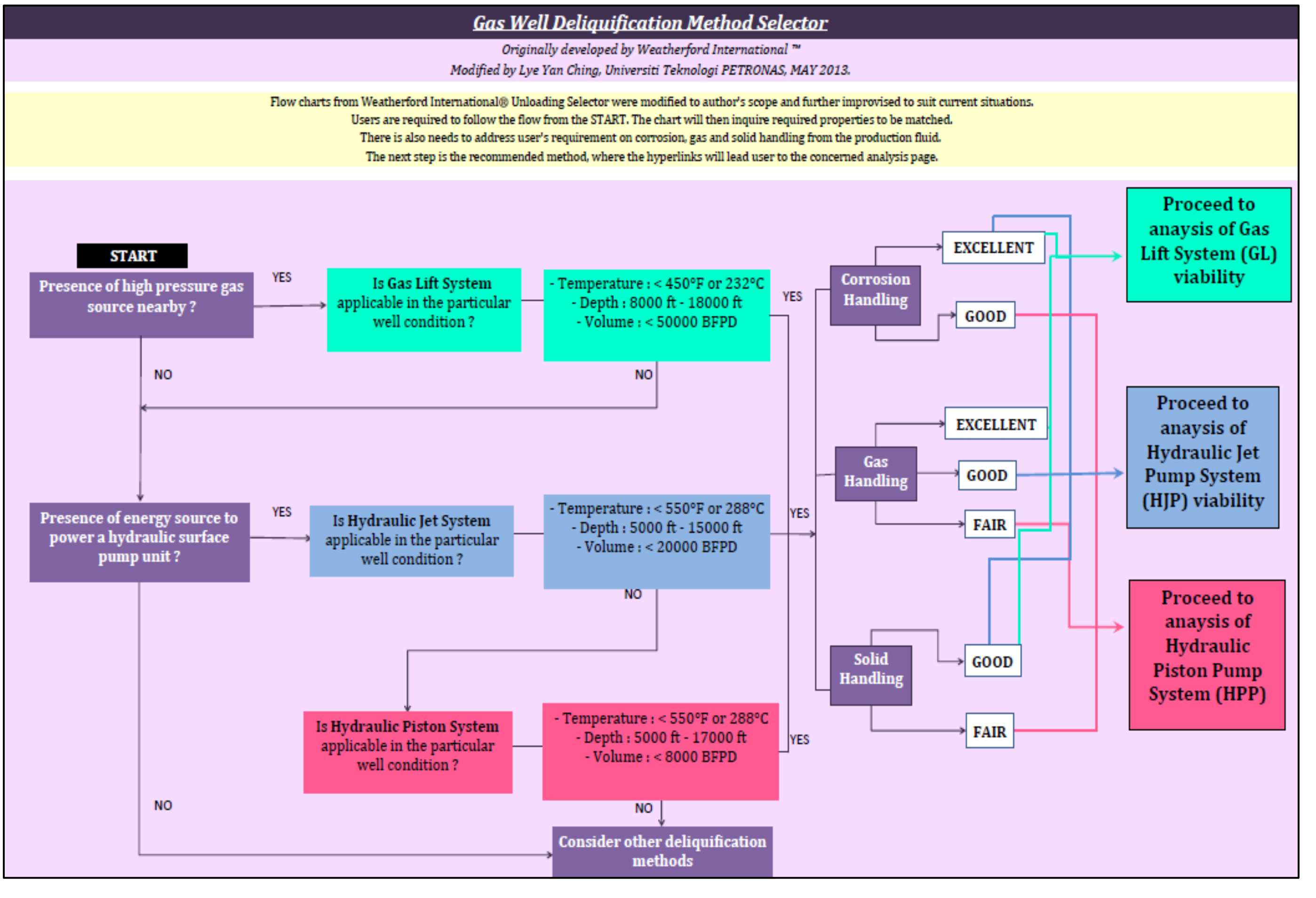


Figure 8: Gas Well Deliquification Method Selector modified and developed by author (STEP 1).

4.4.2 Technical Analysis of Method Selected

This is Step 2 in the whole process of validating feasibility of gas well deliquification method. The final output from Step 1 is selection of either 1 system from the 3 considered:

I. Hydraulic Piston Pump
II. Hydraulic Jet Pump
III. Gas Lift

However, since gas lift is feasible with the presence of high pressure gas source nearby, technical analysis will not be done on the system. Hence, only hydraulic pumping system will be analysed here. The outcomes of this step are:

i. Desired Productivity Index (J)
ii. Maximum Flow Rate, or Absolute Open Flow (AOF)
iii. Required Minimum Hydraulic Horsepower (HHP_{req})

Users should then compare these 3 outcomes with initial production condition, production profile and readily available power source.

According to data extracted from Kpodo's paper [21], the resulting HHPreq is 24.06 hp for hydraulic piston pump and 15.23 hp for hydraulic jet pump. Parameters like power fluid rate, system efficiency and required surface operating pressure, or wellhead pressure affect the resulting HHPreq. As for the desired productivity index, it is very much affected by reservoir pressure, desired production rate, required producing pressure. The technical specifications of both the hydraulic pumping systems have to be abided at all times where range of operating temperature, depth and pressure were set. All the technical specifications and comparisons are tabulated in Section 4.3.

Below are the generated outcome and process, based on values extracted from Reference [2], [3], [21], [22] and [23]. Complete spreadsheet will be attached in Appendix section.

Hydraulic Piston Pump (Technical & Economic Analysis)

Originally developed by Lye Yan Ching

Objectives

To determine technical viability through matching minimum required hydraulic horsepower (HHPreq) with readily available power source.

Legend

Required Input

Generated Output

Part 1 - Technical Analysis

			NOTE
INPUT	Reservoir depth (D):	12000 ft	
	Reservoir pressure (pbar):	4000 psi	Wellbore Pressure
	Desired production rate (qLd):	**750 BLPD**	Max = 8000 BLPD
	Required producing pressure (pwf):	2500 psi	Affects J and AOF
	Power fluid rate (q_{pf}):	300 bbl/day	Affects HHPreq
	Production fluid gravity (°API):	12 °API	Max = 8°API
	Tubing inner diameter (dti):	1.995 in.	
	Power fluid viscosity :	1 cs	Normally is 1cs
	Well head pressure (pwh):	250 psi	Assuming equal to Psurface
	Pump setting depth (Dp):	8700 ft	Between 5000 and 17000ft
	HPP Efficiency (η):	0.55	Normally is 55%
	Power fluid flow system (1 = OPFS, 0 = CPFS):	1	
	Required surface operating pressure :	250 psi	Affects HHPreq
OUTPUT	**Desired productivity index (J):**	**0.5 stb/d.psi**	Compare to initial conditions
	AOF (qmax):	**2000 stb/d**	
	Required min hydraulic horsepower (HHPreq):	**24.06651109 hp**	Match with existing power source

Figure 9: Technical Analysis of Hydraulic Piston Pump developed by author (STEP 2).

Hydraulic Jet Pump (Technical & Economic Analysis)

Originally developed by Lye Yan Ching

Objectives

To determine technical viability through matching minimum required hydraulic horsepower (HHPreq) with readily available power source.

Legend

Required Input

Generated Output

Part 1 - Technical Analysis

			NOTE
INPUT	Reservoir depth (D):	10000 ft	
	Reservoir pressure (pbar):	5000 psi	Wellbore Pressure
	Desired production rate (qLd):	**750 stb/day**	Max = 20000 BLPD
	Required producing pressure (pwf):	3000 psi	Affects J and AOF
	Power fluid rate (q_{pf}):	290 bbl/day	Affects HHPreq
	Production fluid gravity (°API):	12 °API	Max = 8°API
	Tubing inner diameter (dti):	1.995 in.	
	Power fluid viscosity :	1 cs	Normally is 1cs
	Well head pressure (pwh):	300 psi	Assuming equal to Psurface
	Pump setting depth (Dp):	8700 ft	Between 5000 and 15000ft
	HPP Efficiency (η):	0.3	Normally is 30%
	Power fluid flow system (1 = OPFS, 0 = CPFS):	1	
	Required surface operating pressure :	300 psi	Affects HHPreq
OUTPUT	Desire productivity index (J):	0.375 stb/d.psi	Compare to initial conditions
	AOF (qmax):	1875 stb/d	
	Required min hydraulic horsepower (HHPreq):	**15.22753792 hp**	Match with existing power source

Figure 10: Technical Analysis of Hydraulic Jet Pump developed by author (STEP 2).

4.5 Construction and Development of Spreadsheet – Economic Aspect

4.5.1 Economic Analysis

As mentioned in Section 3.5, there are several indicators that can differentiate profitable projects from the rest. Pay-out period, Net present value (NPV) and Internal Rate of return (IRR) [18]. Below is an example for economic analysis made for Hydraulic Piston Pump system. Complete spreadsheet will be attached in Appendix section.

Part 2 - Economic Analysis

Objective

To investigate economic viability through analysing related cash flow, present value (PV) and internal rate of return (IRR).

Economic Indicators

A profitable investment will have a positive NPV. IRR indicates the rate of return earned by this investment.
Profitability is calculated as the rate of return earned by this investment.
Simply stated, it means that over time receipts exceed expenses in today's dollars.

Legend

Required Input
Generated Output

		2013	1993
INPUT	System Used:	Hydraulic Piston Pump	
	Installation Cost ($):	$ 313,522.82	$ 130,000.00
	Initial Production Rate:	1250 mcf/D	
	Increment in Production:	**6.63 MMSCFD**	
	Annual Repair Cost:	$ 24,117.14 / year	$ 10,000.00
	Machine Failure Repair Cost:	$ 48,234.29 / time	$ 20,000.00
	Fuel/ Power Consumption:	$ 164,961.24 / month	$ 68,400.00
	Lifetime of the Machinery:	8 years	
GLOBAL RATE	Gas Price ($):	$ 8.26 / M cf	
	Inflation Rate:	4.50% per year	
OUTPUT	Profit ($):	$ 1,475,943.00 /month	
	Net Present Value ($):	$ 19,739,115.36	
	CONCLUSION:	ECONOMICALLY VIABLE	

Detailed cash flow, pay-out period and IRR are thoroughly tabulated below. Users can now proceed to comparison of this system with the others here >> Economic Comparisons

**Taken in best month, production declines by 50% per year.
* Gas price as of April 2013 ; All costs involved have been brought to present by formulae of PV = Initial value + (Cost *4.5% inflation per year).
*Cash flow of 10 years are presented.
*Production decline = 50% (first 2 years)

Figure 11: Summary of Economic Analysis for Hydraulic Piston Pump – Example (STEP 3).

4.5.2 Pay-out Period

This is frequently used as an indicator of the project's economic merit. It shows the time needed for the project's positive net cash flow to recoup the initial capital outlay. In this project, undiscounted payback method will be used to analyse projects' pay-out period. However, this should not be the main indicator for this project as the profit depends entirely on well production and as time goes by, it is fairly impossible for the operation to maintain the same production. Hence, only ability of project to pay-out for the installation and services are calculated.

For hydraulic pumping system, Amani proposed the total of $129,549, around $ 130,000, for installation of piston pump system, in year 1993. If we bring it to present, year 2013, **assuming inflation rate as 4.5% per year**, it would be total of $313,522.82.

When the pump was installed in Year 3, the production rate was only 1250 mcf/D. After installation of pump, the recovery was 2.42BCF. The increment was 1.19BCF. Given the gas price in 1993 was around $ 8.26/ Thousand Cubic Feet, the increment brought in profit of around $ 1.5 million. Compared to installation costs of $313,000, the pump was perfectly viable. On the same ground, gas lift recovered 0.60 BCF, bringing in $ 1.2 million. Although it is also economically viable, the difference of 1.82 BCF incremental recovery of a pump over gas lift is significant.

Result Summary for Pay out Period and Economic Viability:

- ✓ Hydraulic piston pump is economically viable to be installed. Pay-out period is 1 year.
- ✓ Hydraulic jet pump is economically viable to be installed. Pay-out period is 1 year.
- ✓ Gas lift system is economically viable to be installed. Pay-out period is 1 year.

The snapshots of this section in economic analysis for all 3 systems are shown below:

Cash Flow of: Hydraulic Piston Pump

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition :	$ (313,522.82)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Annual Repair Cost :	$ -	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)
Machine Failure Repair Cost :	$ -	$ -	$ -	$ (48,234.29)	$ (48,234.29)	$ -	$ -	$ -	$ -	$ (48,234.29)	$ (48,234.29)
Fuel/ Power Consumption :	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)
Expenditure :	$ (2,293,057.70)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,051,886.31)	$ (2,051,886.31)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,051,886.31)	$ (2,051,886.31)
Profit :	$ -	$ 17,711,315.98	$ 8,855,657.99	$ 4,427,829.00	$ 3,320,871.75	$ 2,490,653.81	$ 1,867,990.36	$ 1,400,992.77	$ 1,050,744.58	$ 788,058.43	$ 591,043.82
Net Cash Flow :	$ (2,293,057.70)	$ 15,707,663.96	$ 6,852,005.97	$ 2,375,942.69	$ 1,268,985.44	$ 487,001.79	$ (135,661.66)	$ (602,659.25)	$ (952,907.44)	$ (1,263,827.88)	$ (1,460,842.49)
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.955	0.910	0.865	0.820	0.775	0.730	0.685	0.640	0.595	0.550
Present Values :	$ (2,293,057.70)	$ 15,000,819.08	$ 6,235,325.43	$ 2,055,190.42	$ 1,040,568.06	$ 377,426.39	$ (99,033.01)	$ (412,821.59)	$ (609,860.76)	$ (751,977.59)	$ (803,463.37)

Net Present Value : $ 19,739,115.36

Pay-Out Period of : Hydraulic Piston Pump

	Nett	Cumulative
Year 0	$ (2,293,057.70)	$ (2,293,057.70)
1	$ 15,000,819.08	$ 12,707,761.38 PAY-OUT
2	$ 6,235,325.43	$ 18,943,086.81
3	$ 2,055,190.42	$ 20,998,277.24
4	$ 1,040,568.06	$ 22,038,845.29
5	$ 377,426.39	$ 22,416,271.68
6	$ (99,033.01)	$ 22,317,238.67
7	$ (412,821.59)	$ 21,904,417.08
8	$ (609,860.76)	$ 21,294,556.32
9	$ (751,977.59)	$ 20,542,578.73
10	$ (803,463.37)	$ 19,739,115.36

Figure 12: Cash Flow and Pay-out Period for Hydraulic Piston Pump in Economic Analysis (STEP 3).

Cash Flow of : Hydraulic Jet Pump

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition :	$ (241,171.40)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Annual Repair Cost :	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)
Machine Failure Repair Cost :	$ -	$ -	$ -	$ (48,234.28)	$ (48,234.28)	$ -	$ -	$ -	$ -	$ (48,234.28)	$ (48,234.28)
Fuel/ Power Consumption :	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)
Expenditure :	$ (1,220,327.26)	$ (979,155.86)	$ (979,155.86)	$ (1,027,390.14)	$ (1,027,390.14)	$ (979,155.86)	$ (979,155.86)	$ (979,155.86)	$ (979,155.86)	$ (1,027,390.14)	$ (1,027,390.14)
Profit :	$ -	$ 5,988,929.28	$ 5,390,036.35	$ 4,851,032.72	$ 4,365,929.45	$ 3,929,336.50	$ 3,536,402.85	$ 3,182,762.57	$ 2,864,486.31	$ 2,578,037.68	$ 2,320,233.91
Net Cash Flow :	$ (1,220,327.26)	$ 5,009,773.42	$ 4,410,880.49	$ 3,823,642.58	$ 3,338,539.31	$ 2,950,180.64	$ 2,557,246.99	$ 2,203,606.71	$ 1,885,330.45	$ 1,550,647.54	$ 1,292,843.77
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.955	0.910	0.865	0.820	0.775	0.730	0.685	0.640	0.595	0.550
Present Values :	$ (1,220,327.26)	$ 4,784,333.62	$ 4,013,901.25	$ 3,307,450.83	$ 2,737,602.23	$ 2,286,390.00	$ 1,866,790.30	$ 1,509,470.59	$ 1,206,611.49	$ 922,635.29	$ 711,064.07

Net Present Value : $ 22,125,922.40

Pay-Out Period of : Hydraulic Jet Pump

	Nett	Cumulative
Year 0	$ (1,220,327.26)	$ (1,220,327.26)
1	$ 4,784,333.62	$ 3,564,006.36
2	$ 4,013,901.25	$ 7,577,907.60
3	$ 3,307,450.83	$ 10,885,358.43
4	$ 2,737,602.23	$ 13,622,960.66
5	$ 2,286,390.00	$ 15,909,350.66
6	$ 1,866,790.30	$ 17,776,140.96
7	$ 1,509,470.59	$ 19,285,611.56
8	$ 1,206,611.49	$ 20,492,223.04
9	$ 922,635.29	$ 21,414,858.33
10	$ 711,064.07	$ 22,125,922.40

PAY-OUT

Figure 13: Cash Flow and Pay-out Period for Hydraulic Jet Pump in Economic Analysis (STEP 3).

Cash Flow of : Gas Lift

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Construction	$ (85,587.50)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Piping	$ (180,000.00)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Maintenance	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)
Fuel/ Power Consumption :	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)
Expenditure :	$ (1,169,391.02)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)
Profit :	$ -	$ 10,385,720.16	$ 7,789,290.12	$ 5,841,967.59	$ 4,381,475.69	$ 3,286,106.77	$ 2,464,580.08	$ 1,848,435.06	$ 1,386,326.29	$ 1,039,744.72	$ 779,808.54
Net Cash Flow :	$ (1,169,391.02)	$ 9,481,916.64	$ 6,885,486.60	$ 4,938,164.07	$ 3,477,672.17	###########	$1,560,776.56	$ 944,631.54	$ 482,522.77	$ 135,941.20	$ (123,994.98)
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.955	0.910	0.865	0.820	0.775	0.730	0.685	0.640	0.595	0.550
Present Values :	$ (1,169,391.02)	$ 9,055,230.39	$ 6,265,792.81	$ 4,271,511.92	$ 2,851,691.18	$ 1,846,285.02	$ 1,139,366.89	$ 647,072.60	$ 308,814.57	$ 80,885.01	$ (68,197.24)

Net Present Value : $ 25,229,062.14

Pay-Out Period of : Gas Lift

	Nett	Cumulative
Year 0	$ (1,169,391.02)	$ (1,169,391.02)
1	$ 9,055,230.39	$ 7,885,839.37
2	$ 6,265,792.81	$ 14,151,632.18
3	$ 4,271,511.92	$ 18,423,144.10
4	$ 2,851,691.18	$ 21,274,835.28
5	$ 1,846,285.02	$ 23,121,120.30
6	$ 1,139,366.89	$ 24,260,487.18
7	$ 647,072.60	$ 24,907,559.79
8	$ 308,814.57	$ 25,216,374.36
9	$ 80,885.01	$ 25,297,259.38
10	$ (68,197.24)	$ 25,229,062.14

PAY-OUT

Figure 14: Cash Flow and Pay-out Period for Gas Lift System in Economic Analysis (STEP 3).

All three systems use same period of time to recover the investments. This occurs when the cumulative total becomes positive. Hence, this is not the deciding indicator.

4.5.3 Net Present Value (NPV)

The present value of net cash flow occurring at some point in the future, or happened in the past is referred to net present value (NPV) of that cash flow. Sum of money received now is worth more than the same sum of money received several years later in the future. In this project, the discount factor is the inflation rate, which is assumed to be 4.5% per year. Moreover, net present value is calculated, or brought forward to the present (Year 0).

$$Present\ Value = \ Net\ Cash\ Flow\ x\ Inflation\ Rate\ (4.5\%)$$

The NPV results were shown in the Figures 12 to 14 above, by summing up the present values from Year 0 to Year 10. Below are the present values in charts per annum.

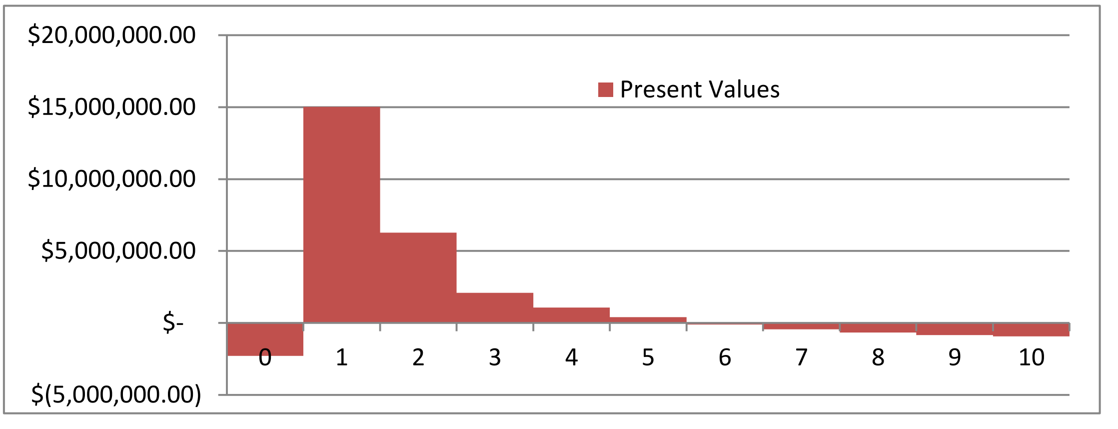


Figure 15: Present Values for 10 years, for HPP system.

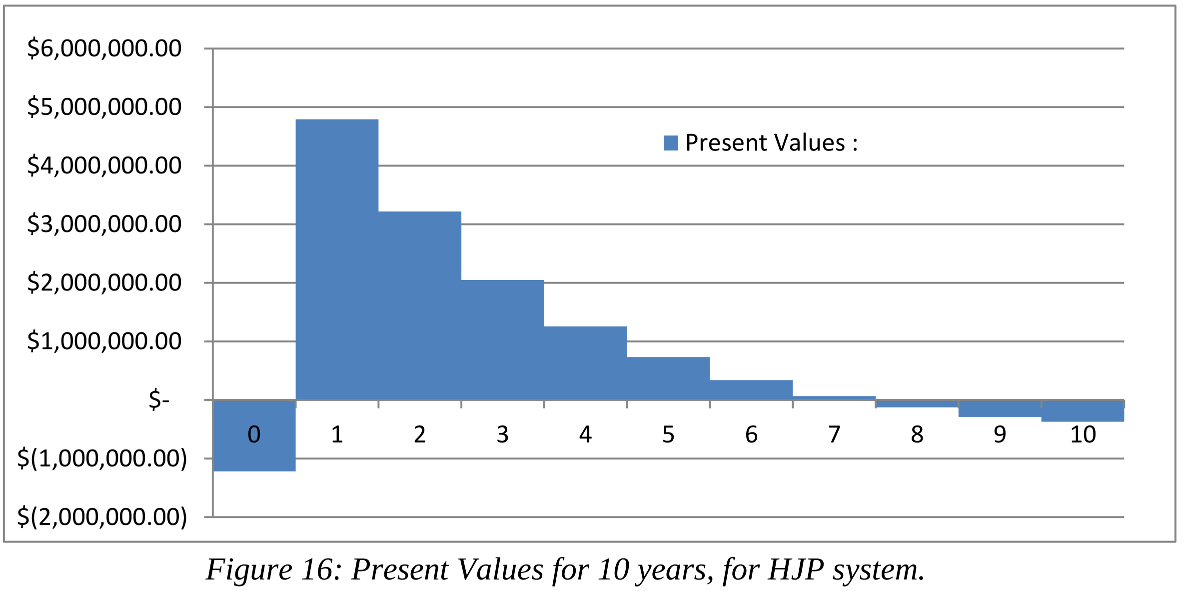


Figure 16: Present Values for 10 years, for HJP system.

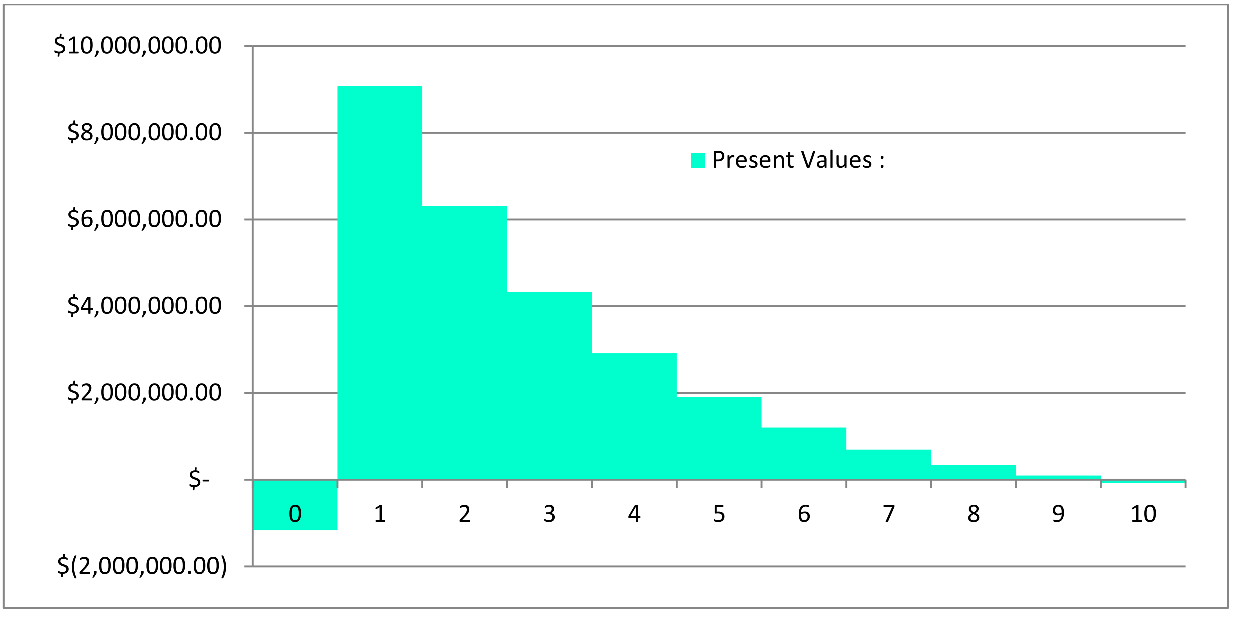


Figure 17: Present Values for 10 years, for Gas Lift system.

Result Summary for Net Present Value, summation of 10 years' Present Values:

- ✓ Hydraulic piston pump: NPV = $19,541,526.69
- ✓ Hydraulic jet pump: NPV = $22,915,124.02
- ✓ **Gas lift system: NPV = $25,608,269.59**

In summary, NPV is a single measure showing the value in excess of Capital Expenditure (CAPEX) and it takes time into account. Gas lift system has the highest NPV of all 3 projects.

4.5.4 Internal Rate of Return (IRR)

The discount rate often used in capital budgeting that makes the net present value of all cash flows from a particular project equal to zero. Generally speaking, the higher a project's internal rate of return, the more desirable it is to undertake the project [20].

From the data extracted from researches and papers published, author managed to generate detailed cash flow which includes Present value, which can then lead to computations of IRRs for all 3 systems. Below are the generated outcome and process, based on values extracted from Reference [2], [3], [21], [22] and [23]. Complete spreadsheet will be attached in Appendix section.

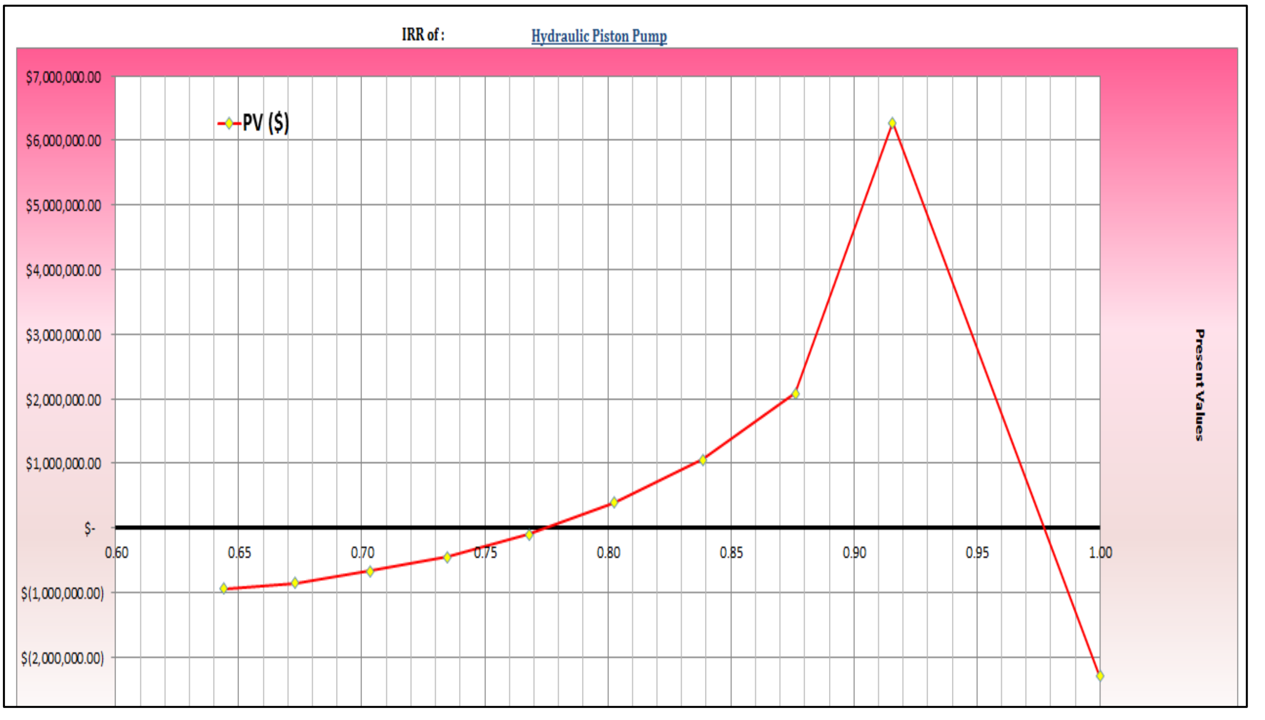


Figure 18: IRRs identified in Spreadsheet using graphical method, for HPP system.

In this Figure, we can observe that there are multiple rates of return as there is more than one intersection with the X-axis, which means the cash flow changes sign twice, the behaviour can be described as follows:

At zero or low discount rates, the NPV is negative. As the discount rates increase, the net cash flow increased drastically hence the drop in value brings minimal significance. At high discount rates, even the discounted positive cash flow is not large enough to offset the negative cash flow at Year 0, hence NPV becomes negative again. IRRs observed here are 77.5% and 97.5%. To relate this situation with real case, lower IRR is taken.

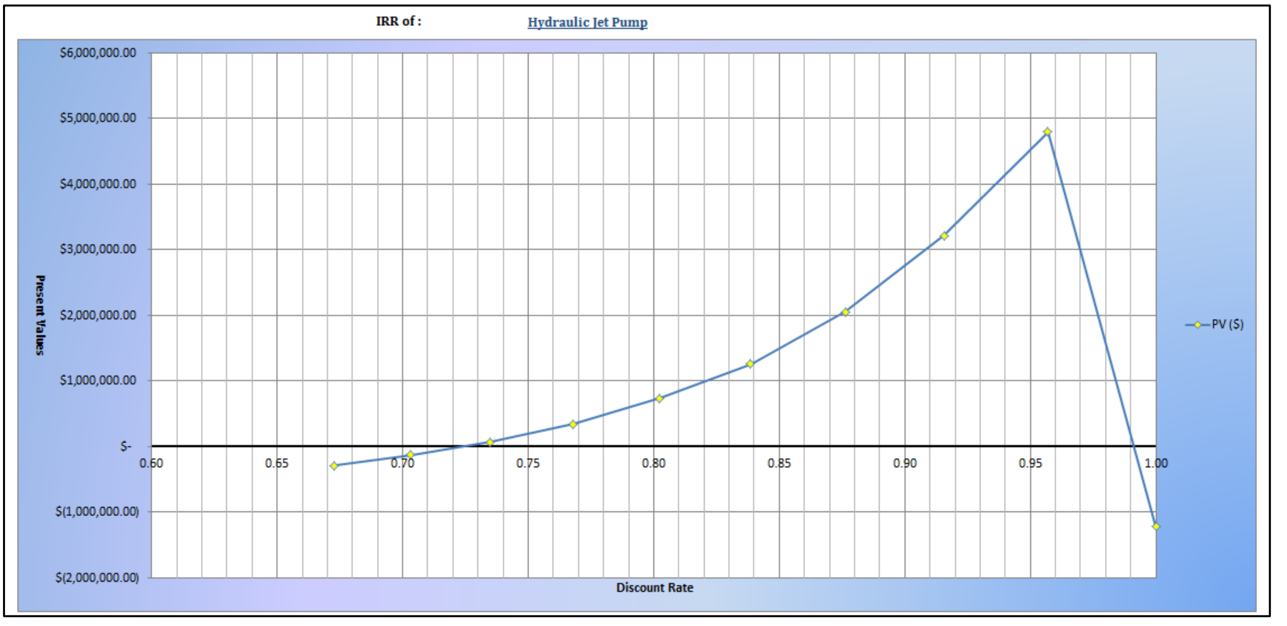


Figure 19: IRRs identified in Spreadsheet using graphical method, for HJP system.

IRRs observed for Hydraulic Jet Pump system are 72.5% and 99.2%. Logically, it should be concluded that the IRR for this system is 72.5%.

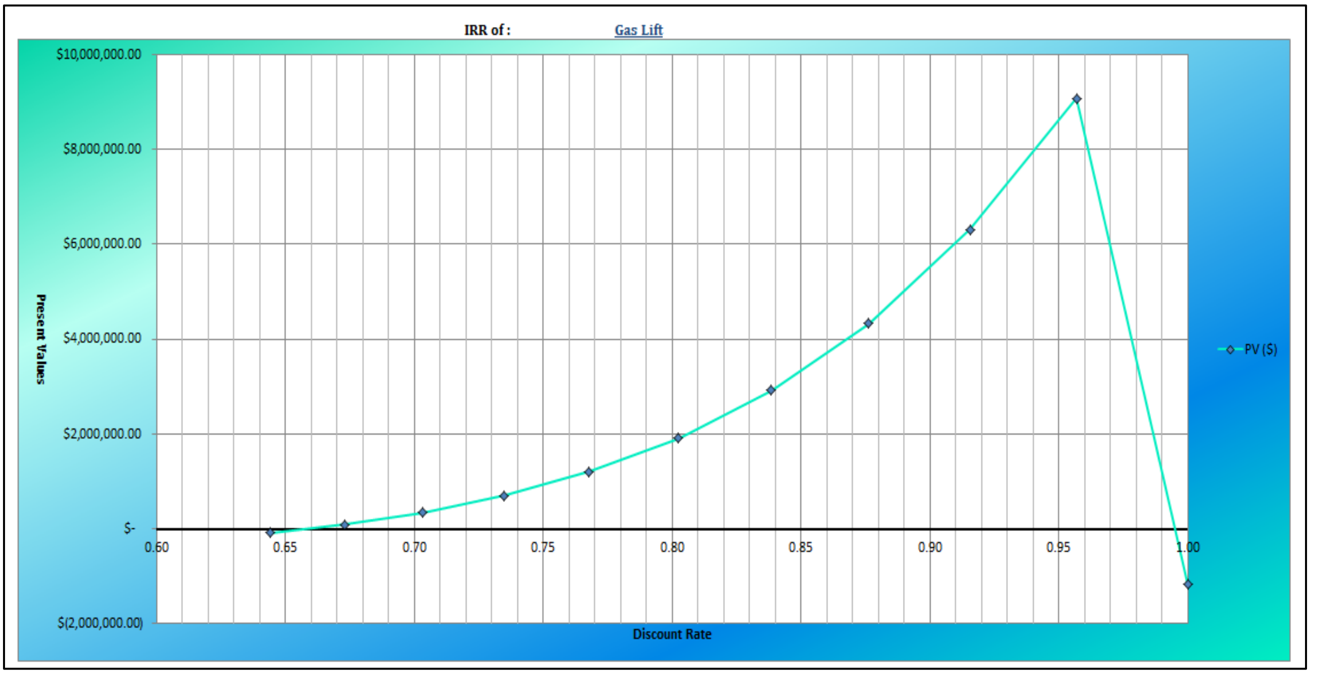


Figure 20: IRRs identified in Spreadsheet using graphical method, for Gas Lift system.

It is observed that the IRRs are 65.5% and 99.5% and 65.5% is taken as the system IRR.

Result Summary for Internal Rate of Return:

- ✓ **Hydraulic piston pump: IRR = 77.5%**
- ✓ Hydraulic jet pump: IRR = 72.5%
- ✓ Gas lift system: IRR = 65.5%

4.6 Comparisons between Deliquification Methods Economically

Comparisons can be made by contrasting 2 economic indicators – NPV and IRR. These projects are mutually exclusive, since they are all deliquifying gas wells, but in different ways. Hence NPV and IRR were tabulated and plotted as to compare and contrast the results.

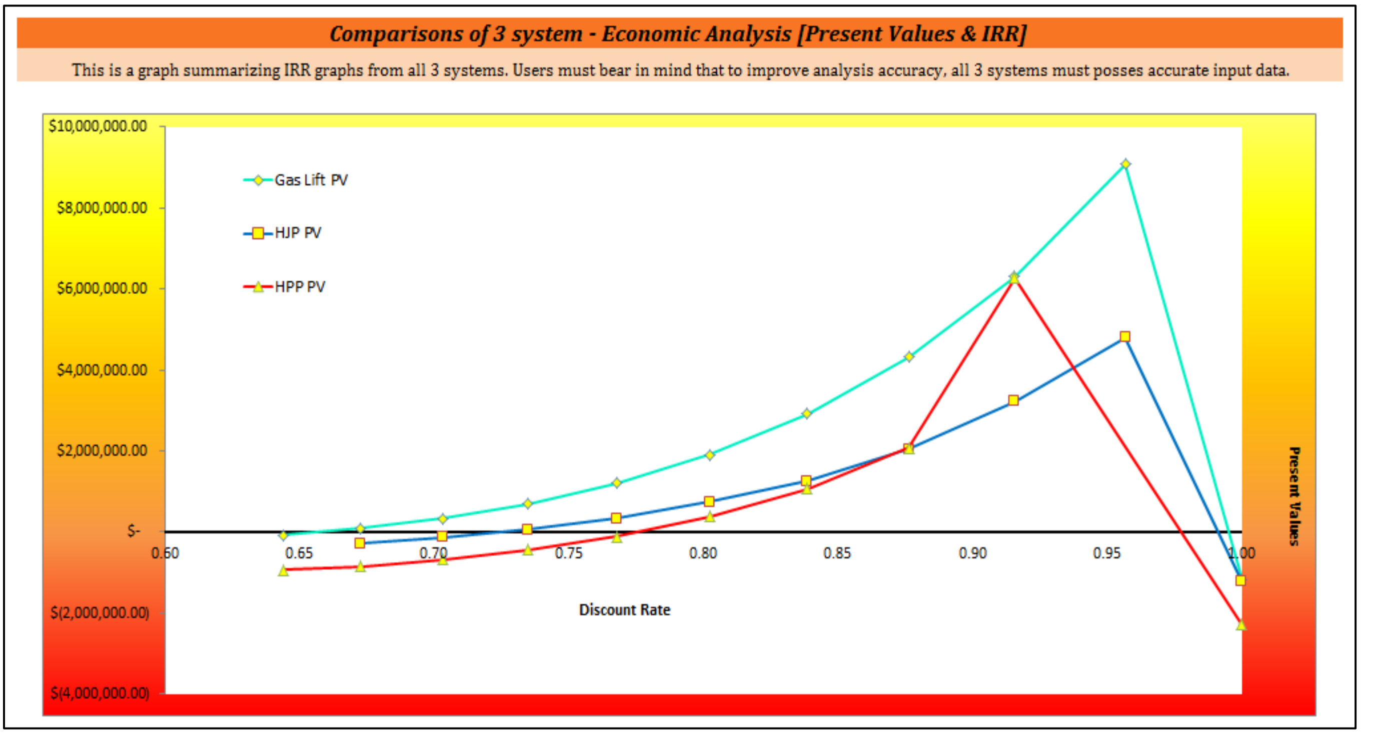


Figure 21: Graphs plotted from all 3 methods for comparison.

From Figure 21, it is clear that Gas Lift system brings in highest cash flow with highest NPV. But Hydraulic Piston Pump has the highest highest IRR. In this situation, the common norm is to choose the project with higher NPV even though the IRR is lower since higher NPV means the company will increase in value by more.

4.7 Sensitivity Analysis

Sensitivity analysis is a technique used to determine how different values of an independent variable will impact a particular dependent variable under a given set of assumptions. This technique is used within specific boundaries that will depend on one or more input variables. Sensitivity analysis is a way to predict the outcome of a decision if a situation turns out to be different compared to the key predictions

Sensitivity analysis is very useful when attempting to determine the impact the actual outcome of a particular variable will have if it differs from what was previously assumed. By creating a given set of scenarios, the analyst can determine how changes in one variable will impact the target variable [31].

➢ 4.7.1 Technical Sensitivity Studies

This sensitivity analysis only involves technical parameters which affect the desired productivity index, absolute open flow (AOF) and required minimum hydraulic horsepower (HHPreq). This analysis is crucial as to increase understanding of the relationships between input and output variables in a system or model.

The outputs can be categorized as:

I. Production output
II. Power requirement

Hence the sensitivity analysis was carried out by involving all parameters which have effect on the outputs above.

Sensitivity Study [Technical Analysis]

Originally developed by Lye Yan Ching

This sensitivity analysis only involves technical parameters which affect the desired productivity index, absolute open flow (AOF) and required minimum hydraulic horsepower (HHPreq).

For economic parameters, please proceed to Economic Sensitivity Study.

Part 1 - Technical Analysis (for Hydraulic Pumps ONLY)

Assumptions							
Reservoir depth (D):	12000	ft	Power fluid viscosity :	1	cs	Power fluid flow system :	1
Production fluid gravity (°API):	12	°API	Well head pressure (pwh):	250	psi		
Tubing inner diameter (dti):	1.995	in	Pump setting depth (Dp):	8700	ft		

Figure 22: Assumptions made for Technical Analysis (STEP 4).

The assumptions above were taken from several papers and researches made on this topic. Values were extracted, modified and some updated to better suit the current situations.

Since technical analysis was made only for hydraulic piston pump and hydraulic jet pump, this technical sensitivity analysis will include the pumps only. Below are the sensitivity studies conducted by the author.

Effect of Reservoir Pressure (pbar)									
	Controlling Variable	Fixed Variables					Resulting Variables		
Set	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	3000	750	2500	300	0.55	250	1.5	4500	24.06651109
2	3200	750	2500	300	0.55	250	1.071428571	3428.571429	24.06651109
3	3500	750	2500	300	0.55	250	0.75	2625	24.06651109
4	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
5	4100	750	2500	300	0.55	250	0.46875	1921.875	24.06651109
6	4200	750	2500	300	0.55	250	0.441176471	1852.941176	24.06651109
7	4300	750	2500	300	0.55	250	0.416666667	1791.666667	24.06651109
8	4500	750	2500	300	0.55	250	0.375	1687.5	24.06651109
9	5000	750	2500	300	0.55	250	0.3	1500	24.06651109
10	7000	750	2500	300	0.55	250	0.166666667	1166.666667	24.06651109

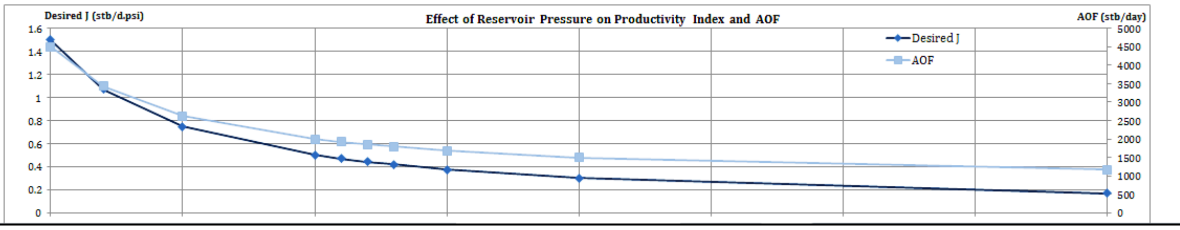


Figure 23: Effect of Reservoir Pressure – Sensitivity Study 1.

From the Figure above, it is obvious that when Reservoir Pressure (Pbar) increases, the desired productivity index (J) decreases and hence, causing maximum flowrate (AOF) to decrease as well. This can be described as follows:

Reservoir Pressure has an **inversely proportional relationship** with Desired Productivity Index and Maximum Flowrate or the AOF.

Effect of Desired Production Rate (qLd)									
	Fixed Variables	Controlling Variable	Fixed Variables				Resulting Variables		
Set	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	4000	400	2500	300	0.55	250	0.266666667	1066.666667	24.06651109
2	4000	450	2500	300	0.55	250	0.3	1200	24.06651109
3	4000	500	2500	300	0.55	250	0.333333333	1333.333333	24.06651109
4	4000	600	2500	300	0.55	250	0.4	1600	24.06651109
5	4000	700	2500	300	0.55	250	0.466666667	1866.666667	24.06651109
6	4000	720	2500	300	0.55	250	0.48	1920	24.06651109
7	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
8	4000	770	2500	300	0.55	250	0.513333333	2053.333333	24.06651109
9	4000	800	2500	300	0.55	250	0.533333333	2133.333333	24.06651109
10	4000	900	2500	300	0.55	250	0.6	2400	24.06651109

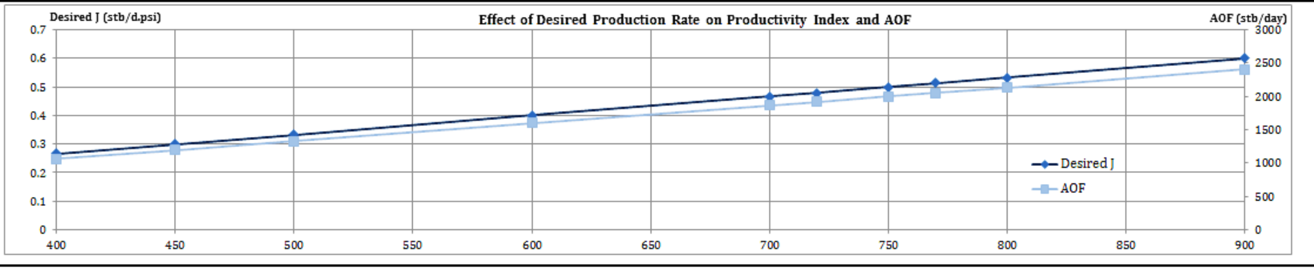


Figure 24: Effect of Desired Production Rate – Sensitivity Study 1.

As for this desired production rate, we can deduce that when it increases, the productivity index increases and the same for AOF.

Hence, Desired Production Rate has a **linear and directly proportional relationship** with Desired Productivity Index and AOF.

Effect of Power Fluid Rate (qpf)									
	Fixed Variables			Controlling Variable	Fixed Variables		Resulting Variables		
Set	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	4000	750	2500	200	0.55	250	0.5	2000	16.04434072
2	4000	750	2500	250	0.55	250	0.5	2000	20.0554259
3	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
4	4000	750	2500	320	0.55	250	0.5	2000	25.67094516
5	4000	750	2500	350	0.55	250	0.5	2000	28.07759627
6	4000	750	2500	370	0.55	250	0.5	2000	29.68203034
7	4000	750	2500	400	0.55	250	0.5	2000	32.08868145
8	4000	750	2500	450	0.55	250	0.5	2000	36.09976663
9	4000	750	2500	500	0.55	250	0.5	2000	40.11085181
10	4000	750	2500	700	0.55	250	0.5	2000	56.15519253

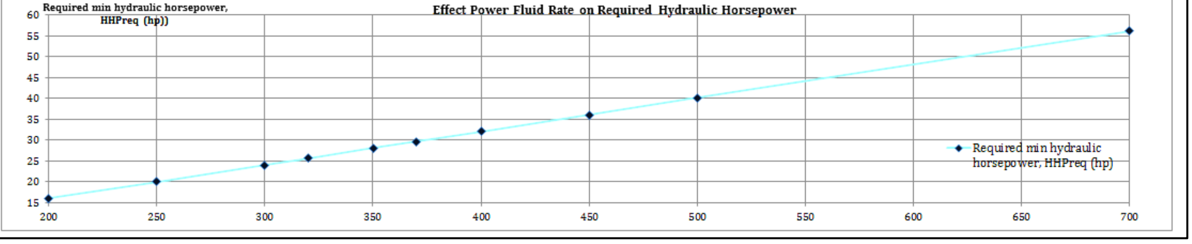


Figure 25: Effect of Power Fluid Rate – Sensitivity Study 1.

This section of study is focussed on the other output, the required minimum hydraulic horsepower (HHPreq). From Figure 25, it is apparent that as the power fluid rate increases, the required horsepower increases as well.

Thus, we can deduce that the Power Fluid Rate has a **directly proportional relationship** with Required Minimum Hydraulic Horsepower.

Effect of Pump Efficiency (η)									
	Fixed Variables				Controlling Variable	Fixed Variables	Resulting Variables		
Set	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	4000	750	2500	300	0.10	250	0.5	2000	4.375729288
2	4000	750	2500	300	0.15	250	0.5	2000	6.563593932
3	4000	750	2500	300	0.20	250	0.5	2000	8.751458576
4	4000	750	2500	300	0.25	250	0.5	2000	10.93932322
5	4000	750	2500	300	0.30	250	0.5	2000	13.12718786
6	4000	750	2500	300	0.35	250	0.5	2000	15.31505251
7	4000	750	2500	300	0.40	250	0.5	2000	17.50291715
8	4000	750	2500	300	0.50	250	0.5	2000	21.87864644
9	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
10	4000	750	2500	300	0.80	250	0.5	2000	35.00583431

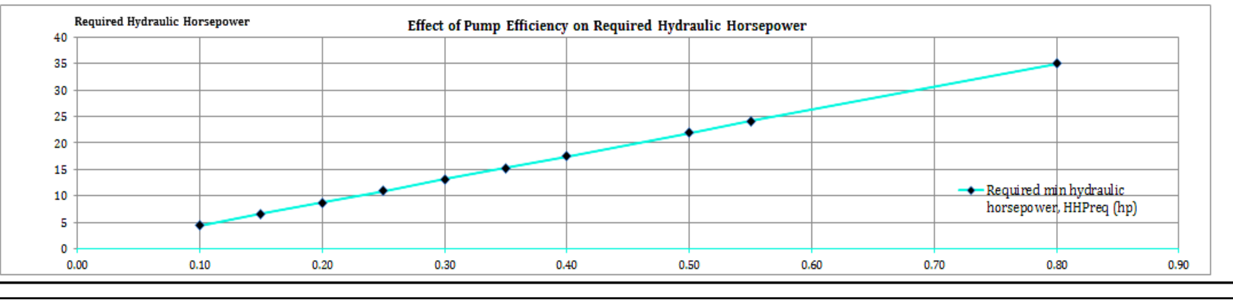


Figure 26: Effect of Pump Efficiency – Sensitivity Study 1.

Pump efficiency is one of the determining factors to express the whole system's performance. In this sensitivity study, we can conclude that as the efficiency increases, the required power to generate the pump is higher too.

Therefore, it is safe to say the Pump Efficiency has a **linear and directly proportional relationship** with Required Minimum Hydraulic Horsepower.

Effect of Surface Operating Pressure									
	Fixed Variables					Controlling Variable	Resulting Variables		
Set	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	4000	750	2500	300	0.55	100	0.5	2000	9.626604434
2	4000	750	2500	300	0.55	120	0.5	2000	11.55192532
3	4000	750	2500	300	0.55	150	0.5	2000	14.43990665
4	4000	750	2500	300	0.55	200	0.5	2000	19.25320887
5	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
6	4000	750	2500	300	0.55	280	0.5	2000	26.95449242
7	4000	750	2500	300	0.55	300	0.5	2000	28.8798133
8	4000	750	2500	300	0.55	400	0.5	2000	38.50641774
9	4000	750	2500	300	0.55	500	0.5	2000	48.13302217
10	4000	750	2500	300	0.55	600	0.5	2000	57.7596266

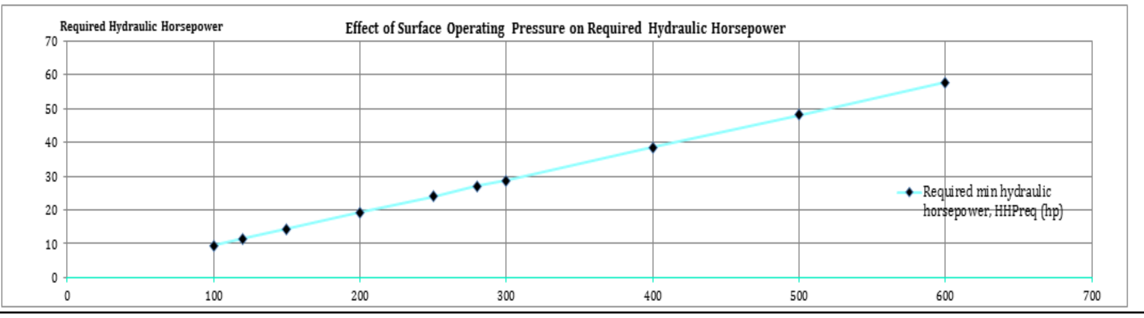


Figure 27: Effect of Surface Operating Pressure – Sensitivity Study 1.

Required surface operating pressure is the wellhead pressure, which is normally dependent on required producing pressure since productivity is very much affected by pressure drawdown between surface and bottomhole pressure. In this sensitivity study, we can observe that as surface operating pressure increases, the required hydraulic horsepower increases consequently.

Hence, the Required Surface Operating Pressure has a **linear and directly proportional relationship** with Required Minimum Hydraulic Horsepower.

➢ 4.7.2 Economic Sensitivity Studies

This sensitivity analysis only involves economic parameters which affect the net profit and economic viability (conclusion).

The economic viability is determined by the profit and the expenses. Below is the sensitivity studies conducted, involving various parameters.

Sensitivity Study [Economic Analysis]

Originally developed by Lye Yan Ching

This sensitivity analysis only involves economic parameters which affect the nett profit and economic viability (conclusion).

For economic parameters, please proceed to Technical Sensitivity Study.

Part 1 - Economic Analysis (for Hydraulic Pumps & Gas Lift System)

Assumptions			
Initial Production Rate:	1250 mcf/D	Gas Price ($):	$ 8.46 / M cf
Lifetime of the Machinery:	8 Years	Inflation Rate:	4.50% per year
Annual Repair Cost:	$ 36,000.00 / year		
Machine Failure Repair Cost:	$ 48,000.00 / time/year		

Figure 28: Assumptions made for Economic Aspects – Sensitivity Study 2.

The assumptions above were taken from several papers, websites and researches made on this topic. Values were extracted, modified and some updated to better suit the current situations.

Below is the sensitivity studies made:

Effect of Installation Cost						
	Controlling Variable	Fixed Variables			Resulting Variables	
Set	Installation Cost ($)	Increment in Production (MMscfd)	Fuel/ Power Consumption ($/month)	Repair & Failure Cost ($/month)	Profit ($/month)	Viability
1	$ 100,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
2	$ 120,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
3	$ 150,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
4	$ 200,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
5	$ 250,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
6	$ 300,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
7	$ 350,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
8	$ 400,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
9	$ 500,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
10	$ 600,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY NOT VIABLE

Figure 29: Effect of Installation Cost – Sensitivity Study 2.

From the Figure above, it is shown that installation cost does not affect profit directly. However, if the installation cost goes above $600,000.00, the system is no longer economically viable as the profit is less than the installation cost itself.

Effect of Production Increment						
Set	Fixed Variables	Controlling Variable	Fixed Variables		Resulting Variables	
	Installation Cost ($)	Increment in Production (MMscfd)	Fuel/ Power Consumption ($/month)	Repair & Failure Cost ($/month)	Profit ($/month)	Viability
1	$ 100,000.00	1.0	$ 85,000.00	$ 7,000.00	$ (32,000.00)	ECONOMICALLY NOT VIABLE
2	$ 100,000.00	1.5	$ 85,000.00	$ 7,000.00	$ (2,000.00)	ECONOMICALLY NOT VIABLE
3	$ 100,000.00	2.0	$ 85,000.00	$ 7,000.00	$ 28,000.00	ECONOMICALLY NOT VIABLE
4	$ 100,000.00	3.0	$ 85,000.00	$ 7,000.00	$ 88,000.00	ECONOMICALLY NOT VIABLE
5	$ 100,000.00	3.5	$ 85,000.00	$ 7,000.00	$ 118,000.00	ECONOMICALLY VIABLE
6	$ 100,000.00	3.7	$ 85,000.00	$ 7,000.00	$ 130,000.00	ECONOMICALLY VIABLE
7	$ 100,000.00	4.0	$ 85,000.00	$ 7,000.00	$ 148,000.00	ECONOMICALLY VIABLE
8	$ 100,000.00	4.2	$ 85,000.00	$ 7,000.00	$ 160,000.00	ECONOMICALLY VIABLE
9	$ 100,000.00	4.5	$ 85,000.00	$ 7,000.00	$ 178,000.00	ECONOMICALLY VIABLE
10	$ 100,000.00	6.0	$ 85,000.00	$ 7,000.00	$ 268,000.00	ECONOMICALLY VIABLE

Figure 30: Effect of Production Increment – Sensitivity Study 2.

Gas well deliquification is to unload liquid and increase gas production, or return to the initial production state. Hence increment in production is a key indicator of performance for the systems. However, the increment has to go over a threshold as to balance the expenditure of installing and running the system.

In the Figure above, it is clear that the production increment has to go above 3.0MMSCFD for the system to be economically viable.

Effect of Power Consumption						
Set	Fixed Variables		Controlling Variable	Fixed Variables	Resulting Variables	
	Installation Cost ($)	Increment in Production (MMscfd)	Fuel/ Power Consumption ($/month)	Repair & Failure Cost ($/month)	Profit ($/month)	Viability
1	$ 100,000.00	4.5	$ 50,000.00	$ 7,000.00	$ 213,000.00	ECONOMICALLY VIABLE
2	$ 100,000.00	4.5	$ 60,000.00	$ 7,000.00	$ 203,000.00	ECONOMICALLY VIABLE
3	$ 100,000.00	4.5	$ 70,000.00	$ 7,000.00	$ 193,000.00	ECONOMICALLY VIABLE
4	$ 100,000.00	4.5	$ 80,000.00	$ 7,000.00	$ 183,000.00	ECONOMICALLY VIABLE
5	$ 100,000.00	4.5	$ 85,000.00	$ 7,000.00	$ 178,000.00	ECONOMICALLY VIABLE
6	$ 100,000.00	4.5	$ 95,000.00	$ 7,000.00	$ 168,000.00	ECONOMICALLY VIABLE
7	$ 100,000.00	4.5	$ 100,000.00	$ 7,000.00	$ 163,000.00	ECONOMICALLY VIABLE
8	$ 100,000.00	4.5	$ 200,000.00	$ 7,000.00	$ 63,000.00	ECONOMICALLY NOT VIABLE
9	$ 100,000.00	4.5	$ 250,000.00	$ 7,000.00	$ 13,000.00	ECONOMICALLY NOT VIABLE
10	$ 100,000.00	4.5	$ 300,000.00	$ 7,000.00	$ (37,000.00)	ECONOMICALLY NOT VIABLE

Figure 31: Effect of Power Consumption – Sensitivity Study 2.

On top of installation cost, the hydraulic pumps are powered by mostly fuel, and hence, costs. The objective of economic analysis is to validate the viability of the system. Hence all positive and negative cash flows need to be included.

In this study, fuel and power consumption should be kept below $ 100,000.00 to keep the system economically viable. If the fuel and power cost exceeds $100,000.00, the system will no longer be feasible, from economic aspect.

4.8 Discussion and Justifications

- ### 4.8.1 Comparative Analysis

Before selecting a gas well deliquification method, there are a lot of factors to be considered. For example, IPR, liquid production rate, water cut, GLR, viscosity, formation volume factor, reservoir drive mechanism, well depth, completion type, casing and tubing sizes, wellbore deviation, flow rates, fluid contaminants, power sources, field location, long-range recovery plans and availability of operating and service personnel. When machines broke down onsite, 65% were caused by human error.

The jet pump is excellent in corrosion resistance while piston pump is less good comparatively. This is due to the higher amount of parts involved in piston pumps. Jet lift system is more compact as compared with piston pump assemblies. Jet lift system hence requires less space, making it more preferable for offshore operations.

The relationships between parameters were clearly stated in the Technical Sensitivity Analysis earlier. The outputs of Desired Productivity Index and Maximum Flowrate (AOF) were studied and their significance was addressed.

- ### 4.8.2 Technical & Economic Analysis

Assumptions made when generating the spreadsheet were:

i. Values were taken from previous studies and published papers found from internet and trusted websites like OnePetro, SPE Online, KNovel and CNN Global for global gas price.

ii. Hydraulic piston pump has the installation costs of nearly $ 320,000. The increment in production is 2.42 BCF/Year. All relevant information and values were taken from Reference [2], [3], and [21].

iii. For hydraulic jet pump, acquisition cost is $ 120,000 and installation cost is $ 120,000. Increment in production is 2.28 MMSCFD and the values were taken from Reference [23] and [24].

iv. As for gas lift system, the installation is fairly higher since additional piping system needs to be installed for the process and that will take up $ 205,000. Construction and management cost for the system is $ 86,000 and the production increment is 3.5 MMSCFD. The information was extracted from Reference [12].

v. All the values were taken from published papers from reliable sources. For the costs, author brought all of them to present time, by computing the costs with global inflation rate of 4.5% per year [30].

vi. The values in spreadsheet, as used by author, are examples as extracted from previous work. All the involved values might change due to different situations. These are merely used as indicators to compare different gas well deliquification systems.

vii. To make a more reliable decision: Use the method that yields the more conservative (lower) NPV [29].

CHAPTER 5
CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The objectives of the project were to compare and contrast hydraulic pumping and gas lift system as gas well deliquification methods. This is attained efficiently and relevant to the field of study. Below are the conclusions made from results acquired:

- The analysis mechanism to validate feasibility of gas well deliquification methods has been developed.
- The detailed comparative studies concluded that for different situations, different methods should be used.
    - For extra heavy crude wells with economic constraint, hydraulic piston pump should be opted since it has higher system efficiency.
    - For deviated offshore wells with high solid contents, hydraulic jet pumps should be chosen.
    - Gas lift is elected when the operating volume is very high in deep offshore wells.
- The sensitivity analysis on several technical and economic parameters was done to study the relationships between parameters.
    - The minimum required hydraulic horsepower can be an indicator to validate operation feasibility of systems.
    - For economic viability, the net profit has to exceed a threshold for the system to be practical.
- It is vital to know the effect of each parameter towards the sustainability of system to be suited in various well conditions.

5.3 Recommendations

The author has identified several improvements to be recommended in gas well deliquification future studies. The recommendations are as follow:

i. This project only focused on 3 methods. Further studies can include more methods in the analysis.

ii. Further studies can embrace the field of petroleum economics and relevant latest innovations.

iii. Further improvise the mechanism developed to include more systems, simplifies the commands, inputs required and made user friendly for suitability of the operation purposes.

Upon the completion of this project, it is a sincere wish that the project would benefit the oil and gas industry for a better and more efficient way of choosing between the 3 methods of gas well deliquification.

REFERENCES

1. A.V. Bondurant B.D. Dotson, P.O. Oyewole, *Getting the Last Gasp: Deliquification of Challenging Gas Wells*, IPTC 11651, 2007, p. 10.
2. Amani Mahmood, *Gas Well De-Watering System and Hydraulic Gas Pump, New Designs and a Discussion on Their Economics*, 1994.
3. Amani Mahmood, *Hydraulic Gas Pump and Has Well De-Watering System: Two New Artificial-Lift Systems*, 1993.
4. Roland van Dort, *Deliquification Technology Maximises Gas Well Production*, 2009.
5. William Hearn, *Gas Well Deliquification*, 2010.
6. James F. Lea Henry V. Nickens, *Solving Gas-Well Liquid-Loading Problems*, 2004.
7. King George E., *Deliquifying Mature Gas Wells*, 2005.
8. Weatherford Hydraulic Pumping Tools [Online] // Weatherford International. - http://www.weatherford.com/dn/WFT198938. Accessed on 23rd February 2013.
9. Weatherford Unloading Selector for Gas Well Deliquification [Online] // Weatherford International. - http://www.weatherford.com/Products/Production/GasWellDeliquification/. Accessed on 23rd February 2013.
10. Rick D. Haydel, Donald J. Brink, William K. Acker, Gary J. Gassiott, *Gas Well De-Watering Method Field Study*, SPE 141036, 2011.
11. G.B. Stephenson, R.P Rouen, M.H. Rosenzweig, Schlumberger, *Gas Well Dewatering: A Coordinated Approach*, SPE 58984, 2000.
12. David B. Foo, *Production Optimization of Gas Wells by Automated Unloading: Case Histories*, SPE 59748, 2000.
13. Ridho R. Algrage, Muchammad R. Alfaqih, Tri. A. Proyantoro, Bhre. A. Alfred, *Experiences, Innovations and Best Practices of Hydraulic Jet Pump (HJP) Application at Remote and Swampy Brown Field in Sembakung Block, Indonesia*, IPTC 16953, 2013.
14. Steven A. Pohler, Willian D. Holmes, Stuart A. Cox, *Annular Velocity Enhancement with Gas Lift as a Deliquification Method for Tight Gas Wells with Long Completion Intervals*, SPE 130256, 2010.
15. Paul D. Newendorp, John M. Campbell, *Decision Methods for Petroleum Investments*, 1975, pp. 129.

16. Kermit E. Brown, H. Dale Beggs, *The Technology of Artificial Lift Methods*, 1977, pp 262.
17. *Economic Indicators,* Petroleum Economics Risk & Fiscal Analysis Course Notes.
18. J. Granados, S. F. Mancilla, *Analysis of Hydraulic-Jet Lift System application on Wells in North Region Assets, AIPRA and AIATG.* SPE 160090, 2012.
19. Economic Analysis [Online] // http://www.investopedia.com, Accessed on 27th June 2013.
20. F.K. Kpodo, *Optimizations in the Design and Operation of an Offshore Hydraulic Pumping System,* SPE, 1988, pp459 – 462.
21. Jess A. Babbit, *Hydraulic Pumping Units Proving Very Successful in Deliquifying Gas Wells in East Texas,* SPE 159346, 2012.
22. Jim Speer, Erik Reissig, *Hydraulic Jet Pumping – A Successful Alternative to Dewatering Gas Wells,* J&J Technical Services LLC, 2007.
23. A. Rehman, N. Soponsakilkaew, O. Bello, G. Falcone, *A Generic Model for Optimizing the Selection of Artificial Lift Methods for Liquid Loaded Gas Wells,* Texas A&M University, SPE 146606, 2011.
24. Peter O. Oyewole, James F. Lea, *Artificial Lift Selection Strategy for the Life of a Gas Well with some Liquid Production*, BP & PL Tech LLC, SPE 115950, 2008.
25. Ade Diar Suhendar, Risdiyanto Kurniawan, Eder Lizacano, *Gas Well Deliquification for Maximizing Recovery from Mature Gas Assets,* VICO Indonesia, IPTC 16915, 2013.
26. B. Dotson, E. Nunez-Paclibon, *Gas Well Liquid Loading From the Power Perspective*, BP America Production Co., SPE 110357, 2011.
27. H. Y. Park, Falcone, G. Teodoriu, *Decision Matrix for Liquid Loading in Gas Wells for a Cost/ Benefit Analysis of Lifting Options,* Journal of Natural Gas Science and Engineering, Volume 1, Issue 3, September 2009, pp 72 – 83.
28. Adjusting Cash Flow Projections for Inflation [Online] // http://zinkpulse.com/adjusting-cash-flow-projections-for-inflation/, Accessed on 3rd July 2013.
29. World Factbook from Central Intelligence Agency [Online] // https://www.cia.gov/library//publications/the-world-factbook/geos/xx.html, Accessed on 25th July 2013.

30. Sensitivity Analysis by Investopedia [Online] // http://www.investopedia.com/terms/s/sensitivityanalysis.asp, Accessed on 26th July 2013.
31. Graph Relationship [Online] // http://www.kineticbooks.com/physics/triallabs/Ideal%20Gas/Analyzing%20data.htm, Accessed on 26th July 2013.

APPENDIX A : COMPARATIVE ANALYSIS RESULTS

Comparisons	**Hydraulic Pump**		**Gas Lift**
	Piston	**Jet**	
Maximum operating depth, TVD	17,000 ft 5,182 m	15,000 ft 4,572 m	18,000 ft 4,878 m
Minimum operating depth, TVD	5,000 ft 1,524 m	5,000 ft 1,524 m	8,000 ft 2,438 m
Maximum operating volume (BFPD)	8,000	20,000	50,000
Maximum operating temperature	550 ℉ 288 ℃	550 ℉ 288 ℃	450 ℉ 232 ℃
Corrosion Handling	Good	**Excellent**	Good to Excellent
Gas Handling	Fair	Good	Excellent
Solids Handling	Fair	Good	Good
Fluid Gravity (°API)	>8 (Extra heavy crude)	>8 (Extra heavy crude)	>15 (Heavy crude)
Servicing	Hydraulic of wireline		Wireline or workover rig
Prime Mover	Multicylinder or electric		Compressor
Offshore Application	Good	Excellent	Excellent
System efficiency	45 – 55% -less mechanical work, less problem	10 – 30% -more sophisticated mechanical components	10 – 30%

APPENDIX B : TECHNICAL AND ECONOMIC ANALYSIS RESULTS

<u>Microsoft Excel 2010 Spreadsheet Developed by Author</u>

I. Description
II. Gas Well Deliquification Selector
III. Hydraulic Piston Pump – Technical Analysis & Economic Analysis
IV. Hydraulic Jet Pump – Technical Analysis & Economic Analysis
V. Gas Lift – Economic Analysis
VI. Comparisons (Summary) of 3 Systems' Economic Analysis
VII. Technical Sensitivity Studies
VIII. Economic Sensitivity Studies

GAS WELL DELIQUIFICATION - SELECTOR FOR HYDRAULIC PUMPING AND GAS LIFT

Developed by Lye Yan Ching (12642)
In partial fulfilment of the requirements
for Bachelor of Engineering (Hons) Degree in Petroleum Engineering
Universiti Teknologi PETRONAS, May 2013.

Description

This template acts as a tool to analyze viability of gas well deliquification method. **3 of many methods will be compared and contrasted**.

Hydraulic Piston Pump, Hydraulic Jet Pump and Gas Lift are three similar method in terms of operation theory.

Output of whether the operation is viable or not will be generated in the end, from technical and economic aspects.

Users will be guided throughout the process, in accordance to steps numbered.

To begin, users shall proceed to the **Gas Well Deliquification Method Selector.**

1.0 Selector

Flow charts from Weatherford International® Unloading Selector were modified to author's scope and further improvised to suit current situations.

Users are required to input Reservoir properties in the first step.

The next step is the availability of facilities nearby the concerned location.

In accordance of the steps above and the flow chart, user will then be lead to the recommended method's analysis book.

Here, the output would be either 1 of these 3 systems :

- **Hydraulic Piston Pump**
- **Hydraulic Jet Pump**
- **Gas Lift**

2.0 Selected Gas Well Deliquification Method

This step consists of 2 parts, the technical analysis for Hydraulic Piston Pump (HPP) and Hydraulic Jet Pump (HJP); and economic analysis for all 3 systems, the HPP, HJP and Gas Lift (GL). Inputs are required to generate the indicators for system viability. Output of technical analysis, the required horsepower will decide the power availability. Economic analysis will provide the conclusion of whether it is viable or not.

Comparisons between the systems' Present Value and IRR are available in t **Comparison book.**

However, to improve the accuracy of analysis. Users are advised to insert relevant values for all 3 systems before proceeding to the comparisons.

3.0 Sensitivity Analysis

There will be 2 types of sensitivity analysis :

- **Technical Sensitivity Analysis**
- **Economic Sensitivity Analysis**

This is to determine the relationships between controlling, fixed and resulting variables.

References

This spreadsheet is generated by Lye Yan Ching for Faculty of Geosciences and Petroleum Engineering, Universitit Teknologi PETRONAS.

As mentioned above, the selector is modified and updated from Weatherford International® Unloading Selector.

The values used in the spreadsheet were extracted from field data, provided by

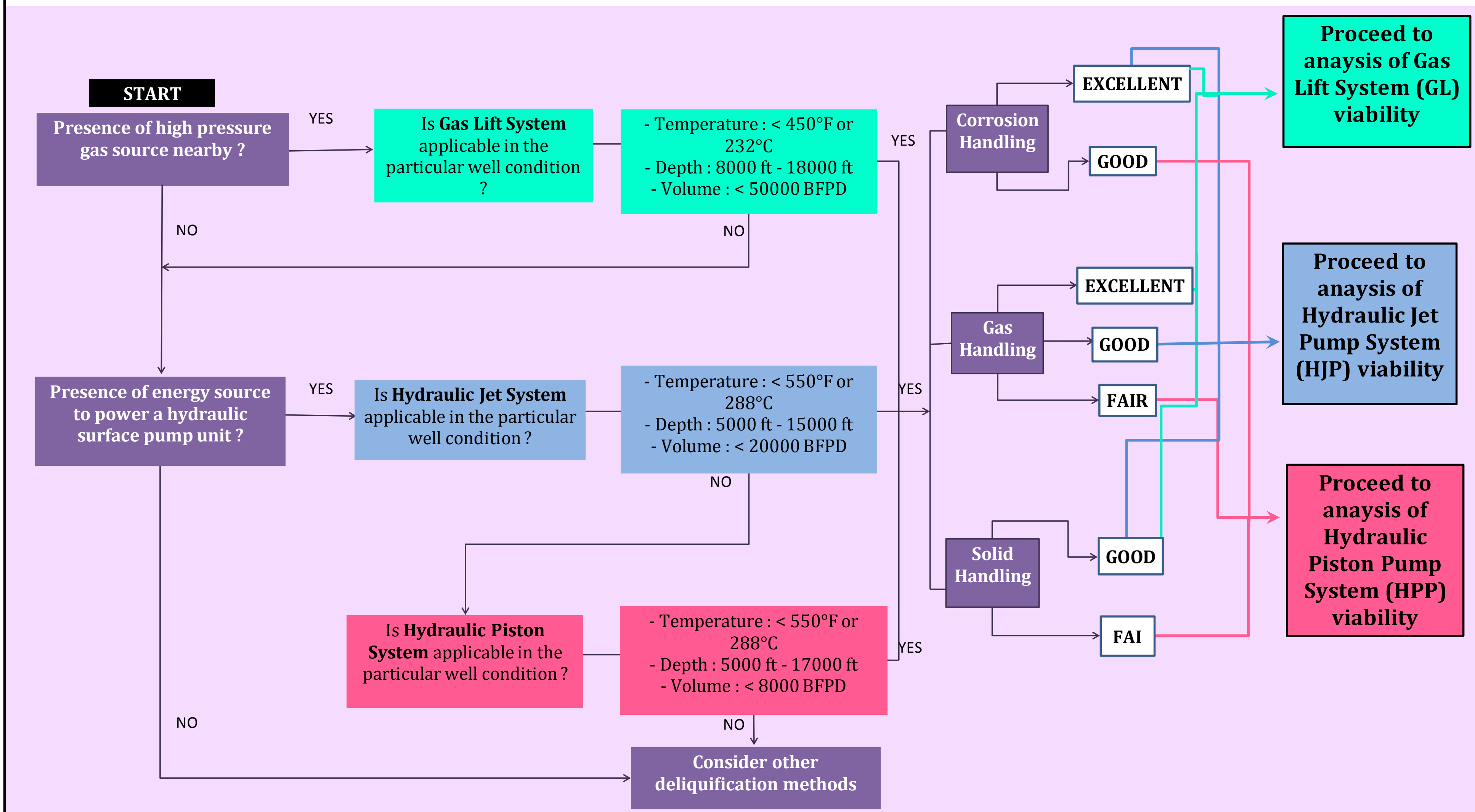
1. Amani Mahmood, *Gas Well De-Watering System and Hydraulic Gas Pump, New Designs and a Discussion on Their Economics* , 1994.
2. Amani Mahmood, *Hydraulic Gas Pump and Has Well De-Watering System: Two New Artificial-Lift Systems* , 1993.
3. G.B. Stephenson, R.P Rouen, M.H. Rosenzweig, Schlumberger, *Gas Well Dewatering: A Coordinated Approach* , SPE 58984, 2000.
4. F.K. Kpodo, *Optimizations in the Design and Operation of an Offshore Hydraulic Pumping System* , SPE, 1988, pp459 – 462.
5. Jess A. Babbit, *Hydraulic Pumping Units Proving Very Successful in Deliquifying Gas Wells in East Texas* , SPE 159346, 2012.
6. Jim Speer, Erik Reissig, *Hydraulic Jet Pumping – A Successful Alternative to Dewatering Gas Wells* , J&J Technical Services LLC, 2007.

Gas Well Deliquification Method Selector

Originally developed by Weatherford International ™

Modified by Lye Yan Ching, Universiti Teknologi PETRONAS, MAY 2013.

Flow charts from Weatherford International® Unloading Selector were modified to author's scope and further improvised to suit current situations.
Users are required to follow the flow from the START. The chart will then inquire required properties to be matched.
There is also needs to address user's requirement on corrosion, gas and solid handling from the production fluid.
The next step is the recommended method, where the hyperlinks will lead user to the concerned analysis page.



Hydraulic Piston Pump (Technical & Economic Analysis)

Originally developed by Lye Yan Ching

Objectives

To determine technical viability through matching minimum required hydraulic horsepower (HHPreq) with readily available power source.

Legend

(blue)	Required Input
(yellow)	Generated Output

Part 1 - Technical Analysis

			NOTE
INPUT	Reservoir depth (D):	12000 ft	
	Reservoir pressure (pbar):	4000 psi	Wellbore Pressure
	Desired production rate (qLd):	**750 BLPD**	Max = 8000 BLPD
	Required producing pressure (pwf):	2500 psi	Affects J and AOF
	Power fluid rate (q_{pf}):	300 bbl/day	Affects HHPreq
	Production fluid gravity (°API):	12 °API	Max = 8°API
	Tubing inner diameter (dti):	1.995 in.	
	Power fluid viscosity :	1 cs	Normally is 1cs
	Well head pressure (pwh):	250 psi	Assuming equal to Psurface
	Pump setting depth (Dp):	8700 ft	Between 5000 and 17000ft
	HPP Efficiency (η):	0.55	Normally is 55%
	Power fluid flow system (1 = OPFS, 0 = CPFS):	1	
	Required surface operating pressure :	250 psi	Affects HHPreq
OUTPUT	**Desired productivity index (J):** **AOF (qmax):**	**0.5 stb/d.psi** **2000 stb/d**	Compare to initial conditions
	Required min hydraulic horsepower (HHPreq):	**24.06651109 hp**	Match with existing power source

Part 2 - Economic Analysis

Objective

To investigate economic viability through analysing related cash flow, present value (PV) and internal rate of return (IRR).

Economic Indicators

A profitable investment will have a positive NPV. IRR indicates the rate of return earned by this investment.
Profitability is calculated as the rate of return earned by this investment.
Simply stated, it means that over time receipts exceed expenses in today's dollars.

Legend

(blue)	Required Input
(yellow)	Generated Output

		2013	1993
INPUT	System Used:	**Hydraulic Piston Pump**	
	Installation Cost ($):	$ 313,522.82	$ 130,000.00
	Initial Production Rate:	1250 mcf/D	
	Increment in Production:	**6.63 MMSCFD**	
	Annual Repair Cost:	$ 24,117.14 / year	$ 10,000.00
	Machine Failure Repair Cost:	$ 48,234.29 / time	$ 20,000.00
	Fuel/ Power Consumption:	$ 164,961.24 / month	$ 68,400.00
	Lifetime of the Machinery:	8 years	
GLOBAL RATE	**Gas Price ($):**	$ 8.26 / M cf	
	Inflation Rate:	4.50% per year	
OUTPUT	**Profit ($):**	**$ 1,475,943.00 /month**	
	Net Present Value ($):	**$ 19,541,526.69**	
	CONCLUSION:	ECONOMICALLY VIABLE	

Detailed cash flow, pay-out period and IRR are thoroughly tabulated below. Users can now proceed to comparison of this system with the others here >> Economic Comparisons

****Taken in best month, production declines by 50% per year.**

*** Gas price as of April 2013 ; All costs involved have been brought to present by formulae of PV = Initial value + (Cost *4.5% inflation per year).**

* Profit/month shown above, is taken from best month of 1 year, hence total profit/ year will be summation of 6 best months and 6 normal (50% less) months.

*Cash flow of 10 years are presented.

*Production decline = 50% (first 2 years), 25% for the rest

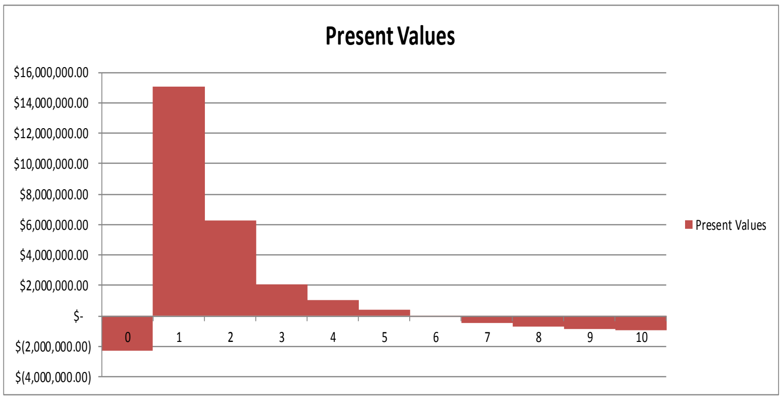
Cash Flow of : Hydraulic Piston Pump

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition :	$ (313,522.82)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Annual Repair Cost :	$ -	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)
Machine Failure Repair Cost :	$ -	$ -	$ -	$ (48,234.29)	$ (48,234.29)	$ -	$ -	$ -	$ -	$ (48,234.29)	$ (48,234.29)
Fuel/ Power Consumption :	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)	$ (1,979,534.88)
Expenditure :	$ (2,293,057.70)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,051,886.31)	$ (2,051,886.31)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,003,652.02)	$ (2,051,886.31)	$ (2,051,886.31)
Profit :	$ -	$ 17,711,315.98	$ 8,855,657.99	$ 4,427,829.00	$ 3,320,871.75	$ 2,490,653.81	$ 1,867,990.36	$ 1,400,992.77	$ 1,050,744.58	$ 788,058.43	$ 591,043.82
Net Cash Flow :	**$ (2,293,057.70)**	**$ 15,707,663.96**	**$ 6,852,005.97**	**$ 2,375,942.69**	**$ 1,268,985.44**	**$ 487,001.79**	**$ (135,661.66)**	**$ (602,659.25)**	**$ (952,907.44)**	**$ (1,263,827.88)**	**$ (1,460,842.49)**
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.957	0.916	0.876	0.839	0.802	0.768	0.735	0.703	0.673	0.644
Present Values :	$ (2,293,057.70)	$ 15,031,257.38	$ 6,274,587.09	$ 2,082,030.51	$ 1,064,122.13	$ 390,795.10	$ (104,174.01)	$ (442,851.17)	$ (670,070.34)	$ (850,435.38)	$ (940,676.92)

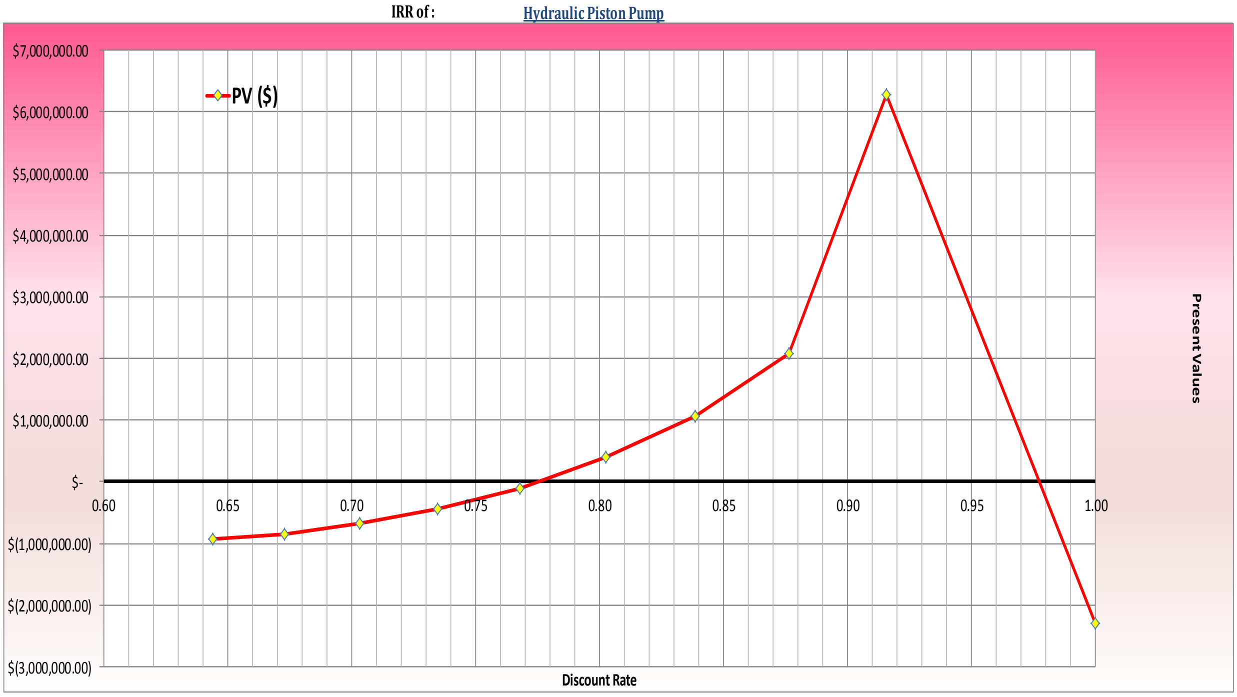
Net Present Value : $ 19,541,526.69

Pay-Out Period of : Hydraulic Piston Pump

	Nett	Cumulative
Year 0	$ (2,293,057.70)	$ (2,293,057.70)
1	$ 15,031,257.38	$ 12,738,199.68
2	$ 6,274,587.09	$ 19,012,786.77
3	$ 2,082,030.51	$ 21,094,817.28
4	$ 1,064,122.13	$ 22,158,939.41
5	$ 390,795.10	$ 22,549,734.51
6	$ (104,174.01)	$ 22,445,560.49
7	$ (442,851.17)	$ 22,002,709.32
8	$ (670,070.34)	$ 21,332,638.98
9	$ (850,435.38)	$ 20,482,203.61
10	$ (940,676.92)	$ 19,541,526.69



IRR of : Hydraulic Piston Pump



Hydraulic Jet Pump (Technical & Economic Analysis)

Originally developed by Lye Yan Ching

Objectives

To determine technical viability through matching minimum required hydraulic horsepower (HHPreq) with readily available power source.

Legend

Required Input
Generated Output

Part 1 - Technical Analysis

			NOTE
INPUT	Reservoir depth (D):	10000 ft	
	Reservoir pressure (pbar):	5000 psi	Wellbore Pressure
	Desired production rate (qLd):	**750 stb/day**	Max = 20000 BLPD
	Required producing pressure (pwf):	3000 psi	Affects J and AOF
	Power fluid rate (q_{pf}):	290 bbl/day	Affects HHPreq
	Production fluid gravity (°API):	12 °API	Max = 8°API
	Tubing inner diameter (dti):	1.995 in.	
	Power fluid viscosity :	1 cs	Normally is 1cs
	Well head pressure (pwh):	300 psi	Assuming equal to Psurface
	Pump setting depth (Dp):	8700 ft	Between 5000 and 15000ft
	HPP Efficiency (η):	0.3	Normally is 30%
	Power fluid flow system (1 = OPFS, 0 = CPFS):	1	
	Required surface operating pressure :	300 psi	Affects HHPreq
OUTPUT	**Desire productivity index (J):**	**0.375 stb/d.psi**	Compare to initial conditions
	AOF (qmax):	**1875 stb/d**	
	Required min hydraulic horsepower (HHPreq):	15.22753792 hp	Match with existing power source

Part 2 - Economic Analysis

Objective

To investigate economic viability through analysing related cash flow, present value (PV) and internal rate of return (IRR).

Economic Indicators

A profitable investment will have a positive NPV. IRR indicates the rate of return earned by this investment.
Profitability is calculated as the rate of return earned by this investment.
Simply stated, it means that over time receipts exceed expenses in today's dollars.

Legend

Required Input
Generated Output

		2013	1993
INPUT	System Used:	**Hydraulic Jet Pump**	
	Acquisition & Installation Cost ($):	$ 241,171.40	$ 100,000.00
	Initial Production Rate:	1400 mcf/D	
	Increment in Production:	**2.28 MMSCFD**	
	Annual Repair Cost:	$ 24,117.14 / year	$ 10,000.00
	Machine Failure Repair Cost:	$ 48,234.28 / time	$ 20,000.00
	Fuel/ Power Consumption:	$ 79,586.56 / month	$ 33,000.00
	Lifetime of the Machinery:	8 years	
GLOBAL RATE	Gas Price ($):	$ 8.46 / M cf	
	Inflation Rate:	4.50% per year	
OUTPUT	**Profit ($):**	**$ 499,077.44 /month**	
	Net Present Value ($):	**$ 10,450,944.23**	
	CONCLUSION:	ECONOMICALLY VIABLE	

Detailed cash flow, pay-out period and IRR are thoroughly tabulated below. Users can now proceed to comparison of this system with the others here >> Economic Comparisons

****Taken in best month, production declines by 50% per year.**

*** Gas price as of April 2013 ; All costs involved have been brought to present by formulae of PV = Initial value + (Cost *4.5% inflation per year).**

*Cash flow of 10 years are presented.

*Machine failure occurs after lifetime

*Production decline = 25%

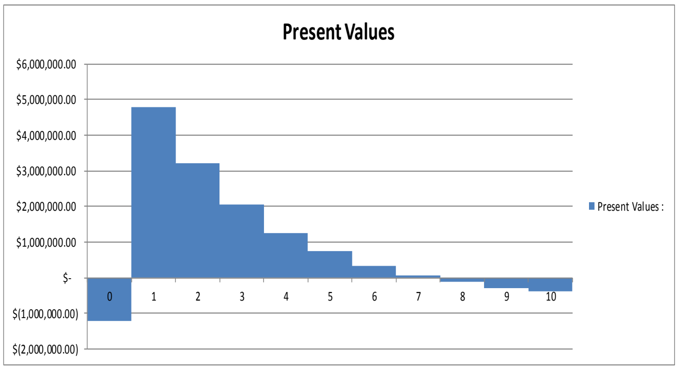
Cash Flow of : Hydraulic Jet Pump

	Year										
	0	1	2	3	4	5	6	7	8	9	10
Acquisition :	$ (241,171.40)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Annual Repair Cost :	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)	$ (24,117.14)
Machine Failure Repair Cost :	$ -	$ -	$ -	$ (48,234.28)	$ (48,234.28)	$ -	$ -	$ -	$ -	$ (48,234.28)	$ (48,234.28)
Fuel/ Power Consumption :	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)	$ (955,038.72)
Expenditure :	$ (1,220,327.26)	$ (979,155.86)	$ (979,155.86)	$ (1,027,390.14)	$ (1,027,390.14)	$ (979,155.86)	$ (979,155.86)	$ (979,155.86)	$ (979,155.86)	$ (1,027,390.14)	$ (1,027,390.14)
Profit :	$ -	$ 5,988,929.28	$ 4,491,696.96	$ 3,368,772.72	$ 2,526,579.54	$ 1,894,934.66	$ 1,421,200.99	$ 1,065,900.74	$ 799,425.56	$ 599,569.17	$ 449,676.88
Net Cash Flow :	$ (1,220,327.26)	$ 5,009,773.42	$ 3,512,541.10	$ 2,341,382.58	$ 1,499,189.40	$ 915,778.80	$ 442,045.13	$ 86,744.88	$ (179,730.30)	$ (427,820.97)	$ (577,713.26)
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.957	0.916	0.876	0.839	0.802	0.768	0.735	0.703	0.673	0.644
Present Values :	$ (1,220,327.26)	$ 4,794,041.55	$ 3,216,539.09	$ 2,051,745.60	$ 1,257,162.28	$ 734,867.65	$ 339,444.57	$ 63,742.61	$ (126,383.68)	$ (287,882.63)	$ (372,005.56)

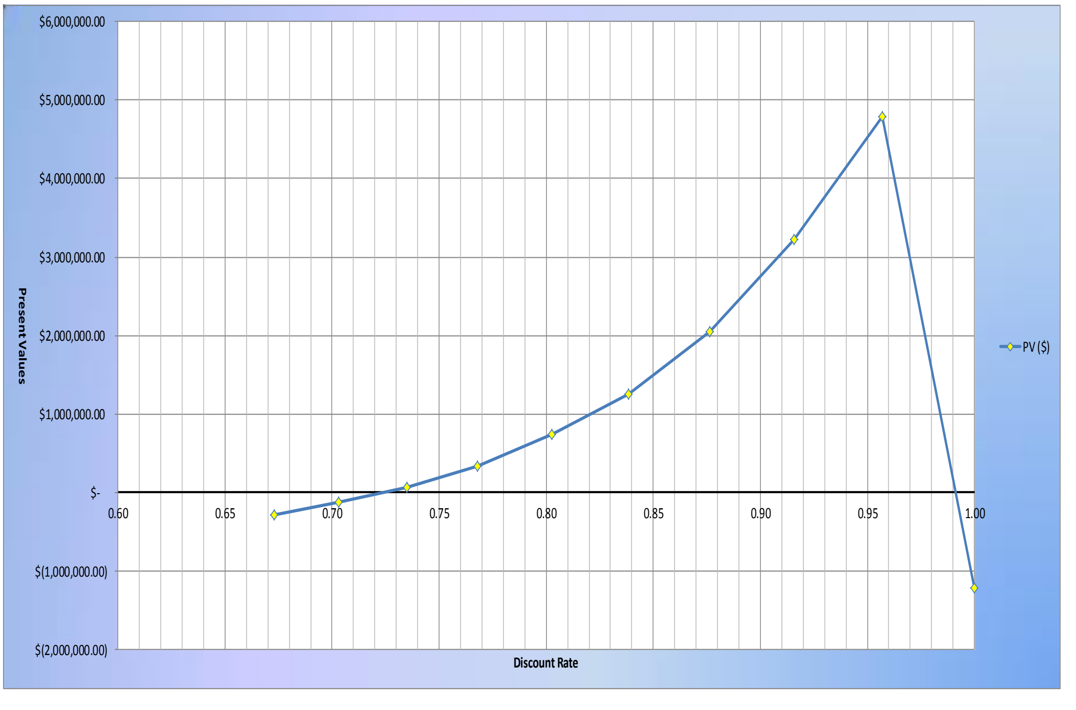
Net Present Value : $ 10,450,944.23

Pay-Out Period of : Hydraulic Jet Pump

	Nett	Cumulative
Year 0	$ (1,220,327.26)	$ (1,220,327.26)
1	$ 4,794,041.55	$ 3,573,714.29
2	$ 3,216,539.09	$ 6,790,253.38
3	$ 2,051,745.60	$ 8,841,998.98
4	$ 1,257,162.28	$ 10,099,161.26
5	$ 734,867.65	$ 10,834,028.91
6	$ 339,444.57	$ 11,173,473.49
7	$ 63,742.61	$ 11,237,216.10
8	$ (126,383.68)	$ 11,110,832.42
9	$ (287,882.63)	$ 10,822,949.79
10	$ (372,005.56)	$ 10,450,944.23



IRR of : Hydraulic Jet Pump



Gas Lift (Economic Analysis)

Originally developed by Lye Yan Ching

Objective

To investigate economic viability through analysing related cash flow, present value (PV) and internal rate of return (IRR).

Economic Indicators

A profitable investment will have a positive NPV. IRR indicates the rate of return earned by this investment.
Profitability is calculated as the rate of return earned by this investment.
Simply stated, it means that over time receipts exceed expenses in today's dollars.

Legend

(blue)	Required Input
(yellow)	Generated Output

Economic Analysis

		2013	2010
INPUT	System Used:	Gas Lift	
	Construction & Management Cost ($):	$ 85,587.50	$ 75,000.00
	Initial Production Rate:	1390 mcf/D	
	Increment in Production:	3.5 MMSCFD	
	Additional Installation (Piping):	$ 205,409.90	$ 180,000.00
	Maintenance Cost:	$ 52,493.64 / month	$ 46,000.00
	Fuel/ Power Consumption:	$ 22,823.32 / month	$ 20,000.00
	Lifetime of the Machinery:	8 years	
GLOBAL RATE	Gas Price ($):	$ 8.46 / M cf	
	Inflation Rate:	4.50% per year	
OUTPUT	**Profit ($):**	**$ 865,476.68 /month**	
	Net Present Value ($):	**$ 25,608,269.59**	
	CONCLUSION:	ECONOMICALLY VIABLE	

Detailed cash flow, pay-out period and IRR are thoroughly tabulated below. Users can now proceed to comparison of this system with the others here >> Economic Comparisons

****Taken in best month, production declines by 50% per year.**

*** Gas price as of April 2013 ; All costs involved have been brought to present by formulae of PV = Initial value + (Cost *4.5% inflation per year).**

*Cash flow of 10 years are presented.

*Machine failure occurs after lifetime

*Production decline = 25%

Cash Flow of : Gas Lift

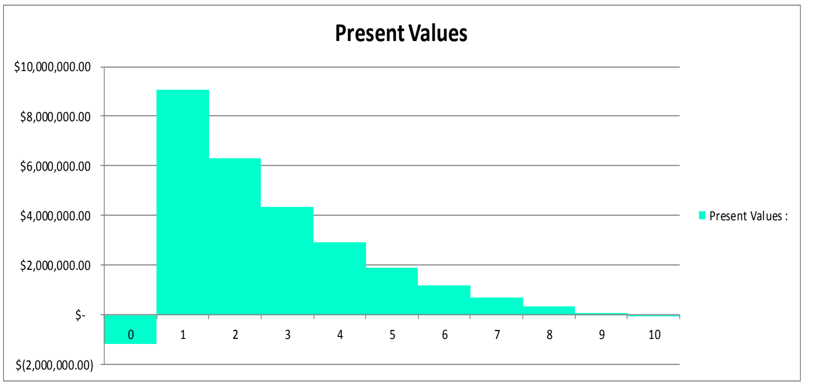
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Construction	$ (85,587.50)	$ -	$ -	$ -	$ -	$ -
Piping	$ (180,000.00)	$ -	$ -	$ -	$ -	$ -
Maintenance	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)
Fuel/ Power Consumption :	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)
Expenditure :	$ (1,169,391.02)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)
Profit :	$ -	$ 10,385,720.16	$ 7,789,290.12	$ 5,841,967.59	$ 4,381,475.69	$ 3,286,106.77
Net Cash Flow :	**$ (1,169,391.02)**	**$ 9,481,916.64**	**$ 6,885,486.60**	**$ 4,938,164.07**	**$ 3,477,672.17**	**$2,382,303.25**
Inflation Rate :	0	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	1.00	0.957	0.916	0.876	0.839	0.802
Present Values :	$ (1,169,391.02)	$ 9,073,604.44	$ 6,305,246.31	$ 4,327,296.40	$ 2,916,241.45	$ 1,911,681.74

	Year 6	Year 7	Year 8	Year 9	Year 10
Construction	$ -	$ -	$ -	$ -	$ -
Piping	$ -	$ -	$ -	$ -	$ -
Maintenance	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)	$ (629,923.68)
Fuel/ Power Consumption :	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)	$ (273,879.84)
Expenditure :	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)	$ (903,803.52)
Profit :	$ 2,464,580.08	$ 1,848,435.06	$ 1,386,326.29	$ 1,039,744.72	$ 779,808.54
Net Cash Flow :	**$1,560,776.56**	**$ 944,631.54**	**$ 482,522.77**	**$ 135,941.20**	**$ (123,994.98)**
Inflation Rate :	4.5%	4.5%	4.5%	4.5%	4.5%
Inflation Factor :	0.768	0.735	0.703	0.673	0.644
Present Values :	$ 1,198,513.67	$ 694,142.14	$ 339,302.84	$ 91,475.44	$ (79,843.80)

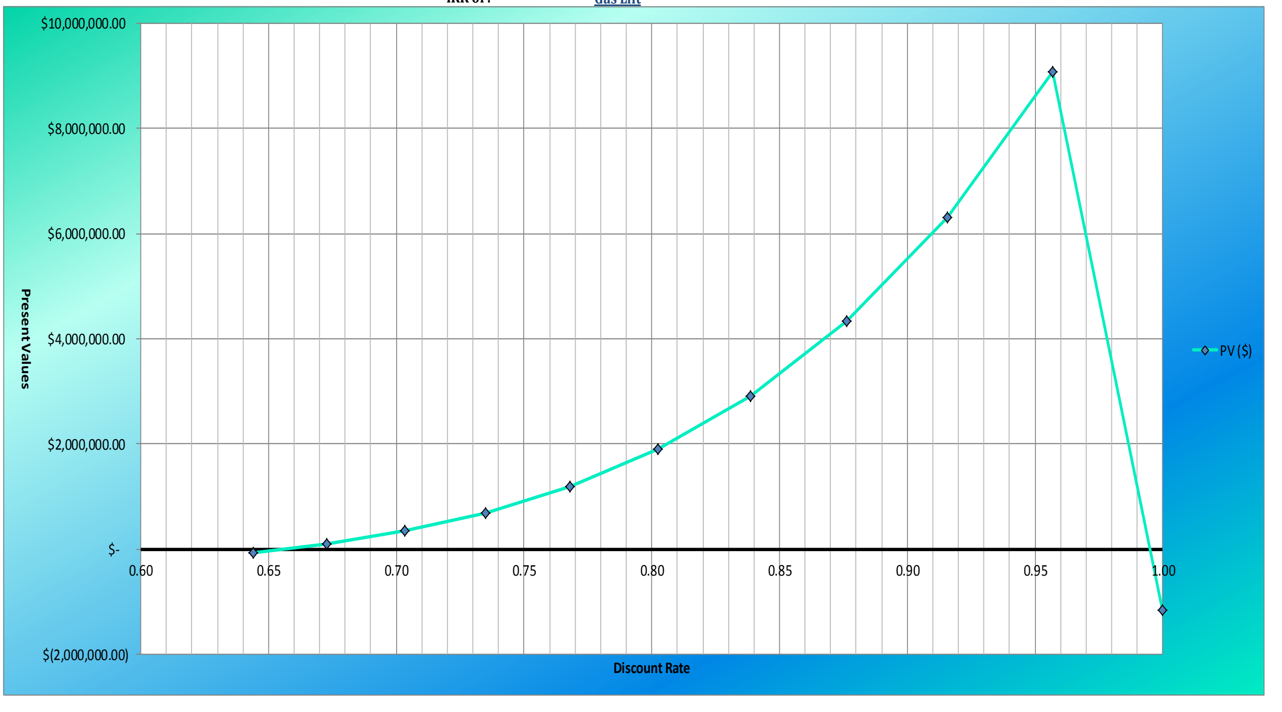
Net Present Value : $ 25,608,269.59

Pay-Out Period of : Gas Lift

	Nett	Cumulative
Year 0	$ (1,169,391.02)	$ (1,169,391.02)
1	$ 9,073,604.44	$ 7,904,213.42
2	$ 6,305,246.31	$ 14,209,459.73
3	$ 4,327,296.40	$ 18,536,756.13
4	$ 2,916,241.45	$ 21,452,997.58
5	$ 1,911,681.74	$ 23,364,679.32
6	$ 1,198,513.67	$ 24,563,192.99
7	$ 694,142.14	$ 25,257,335.12
8	$ 339,302.84	$ 25,596,637.96
9	$ 91,475.44	$ 25,688,113.39
10	$ (79,843.80)	$ 25,608,269.59

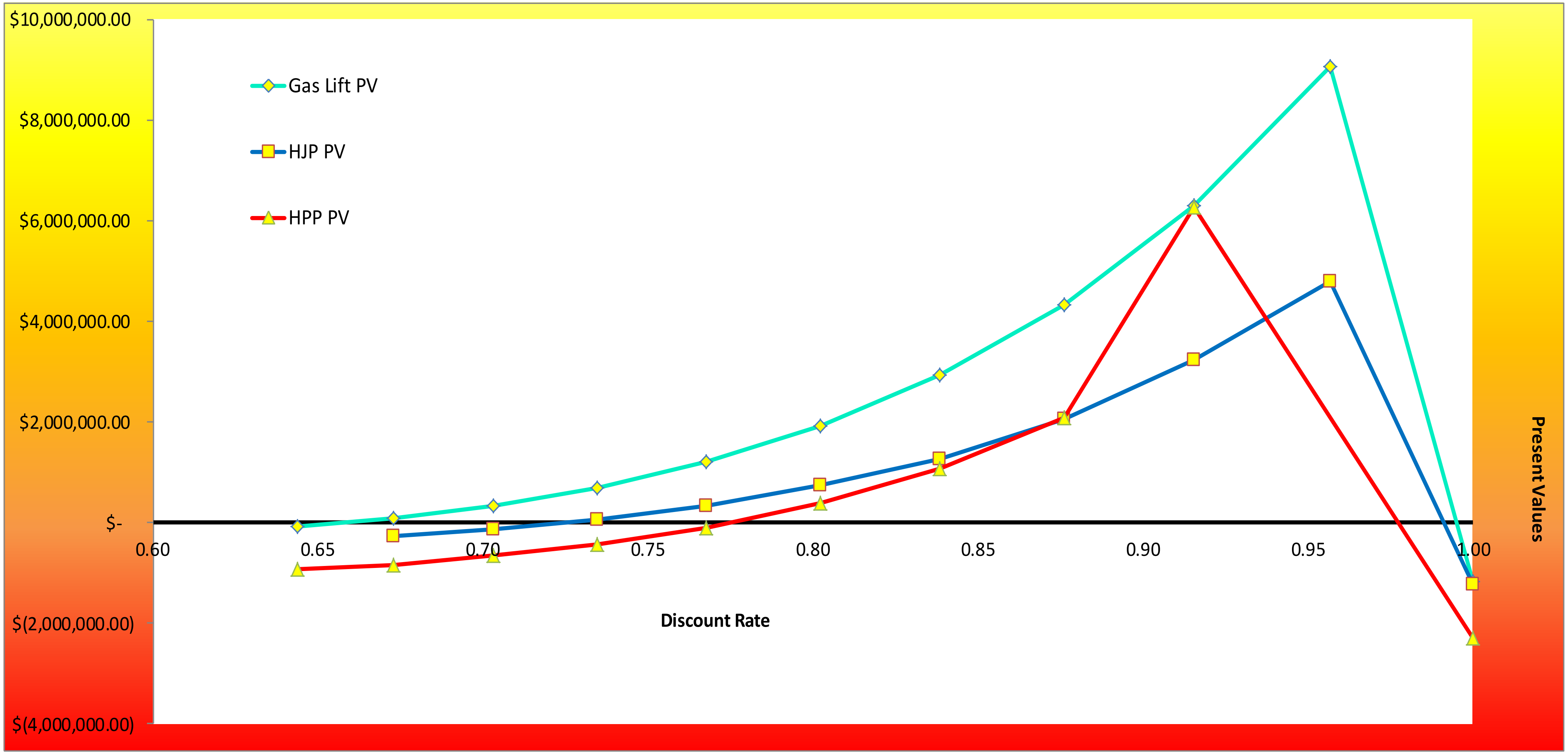


IRR of : Gas Lift



Comparisons of 3 system - Economic Analysis [Present Values & IRR]

This is a graph summarizing IRR graphs from all 3 systems. Users must bear in mind that to improve analysis accuracy, all 3 systems must posses accurate input data.



Sensitivity Study [Technical Analysis]

Originally developed by Lye Yan Ching

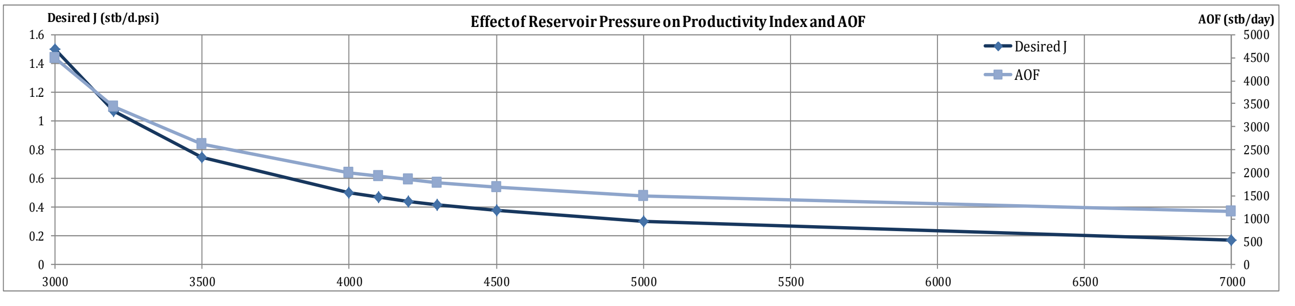
This sensitivity analysis only involves technical parameters which affect the desired productivity index, absolute open flow (AOF) and required minimum hydraulic horsepower (HHPreq).
For economic parameters, please proceed to **Economic Sensitivity Study.**

Part 1 - Technical Analysis (for Hydraulic Pumps ONLY)

Assumptions								
Reservoir depth (D):	12000	ft	Power fluid viscosity :	1	cs	Power fluid flow system :	1	
Production fluid gravity (°API):	12	°API	Well head pressure (pwh):	250	psi			
Tubing inner diameter (dti):	1.995	in	Pump setting depth (Dp):	8700	ft			

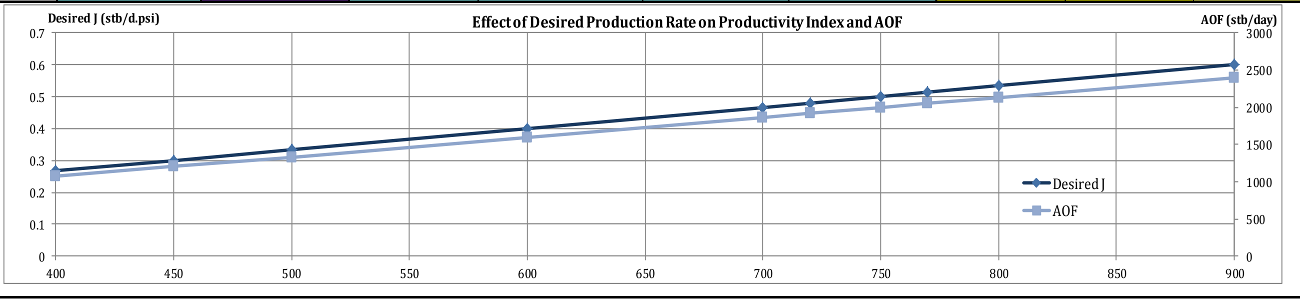
Effect of Reservoir Pressure (pbar)

Set	Controlling Variable	Fixed Variables					Resulting Variables		
	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	3000	750	2500	300	0.55	250	1.5	4500	24.06651109
2	3200	750	2500	300	0.55	250	1.071428571	3428.571429	24.06651109
3	3500	750	2500	300	0.55	250	0.75	2625	24.06651109
4	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
5	4100	750	2500	300	0.55	250	0.46875	1921.875	24.06651109
6	4200	750	2500	300	0.55	250	0.441176471	1852.941176	24.06651109
7	4300	750	2500	300	0.55	250	0.416666667	1791.666667	24.06651109
8	4500	750	2500	300	0.55	250	0.375	1687.5	24.06651109
9	5000	750	2500	300	0.55	250	0.3	1500	24.06651109
10	7000	750	2500	300	0.55	250	0.166666667	1166.666667	24.06651109



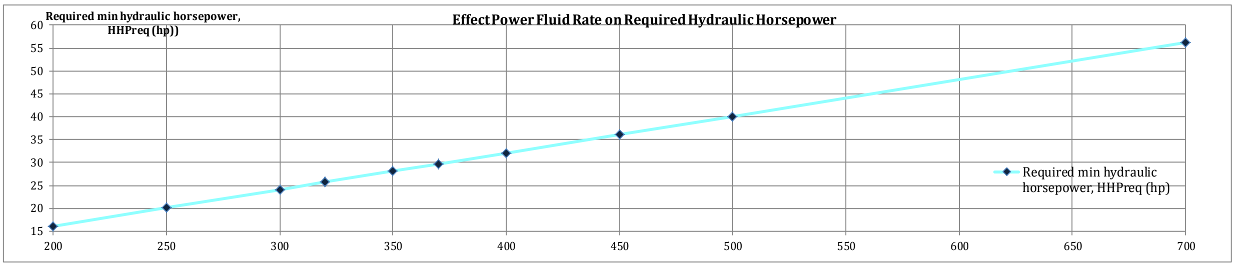
Effect of Desired Production Rate (qLd)

Set	Fixed Variables	Controlling Variable	Fixed Variables				Resulting Variables		
	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	Required min hydraulic horsepower, HHPreq (hp)
1	4000	400	2500	300	0.55	250	0.266666667	1066.666667	24.06651109
2	4000	450	2500	300	0.55	250	0.3	1200	24.06651109
3	4000	500	2500	300	0.55	250	0.333333333	1333.333333	24.06651109
4	4000	600	2500	300	0.55	250	0.4	1600	24.06651109
5	4000	700	2500	300	0.55	250	0.466666667	1866.666667	24.06651109
6	4000	720	2500	300	0.55	250	0.48	1920	24.06651109
7	4000	750	2500	300	0.55	250	0.5	2000	24.06651109
8	4000	770	2500	300	0.55	250	0.513333333	2053.333333	24.06651109
9	4000	800	2500	300	0.55	250	0.533333333	2133.333333	24.06651109
10	4000	900	2500	300	0.55	250	0.6	2400	24.06651109



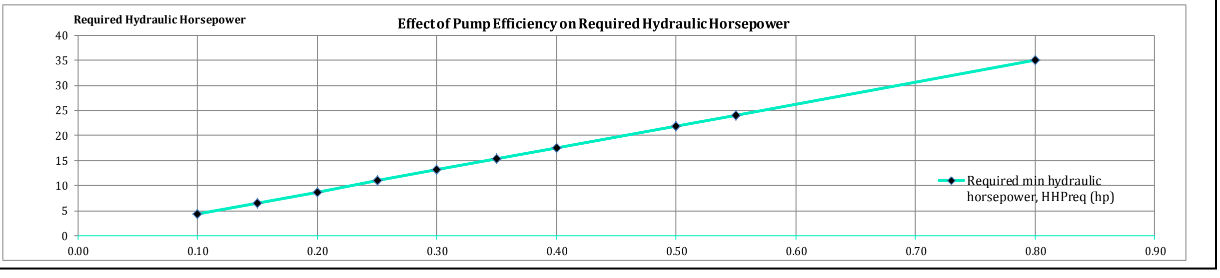
Effect of Power Fluid Rate (qpf)

Set	Fixed Variables			Controlling Variable	Fixed Variables		Resulting Variables		
	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	**Power fluid rate, q_{pf} (bbl/day)**	Pump Efficiency, η	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	**Required min hydraulic horsepower, HHPreq (hp)**
1	4000	750	2500	**200**	0.55	250	0.5	2000	**16.04434072**
2	4000	750	2500	**250**	0.55	250	0.5	2000	**20.0554259**
3	4000	750	2500	**300**	0.55	250	0.5	2000	**24.06651109**
4	4000	750	2500	**320**	0.55	250	0.5	2000	**25.67094516**
5	4000	750	2500	**350**	0.55	250	0.5	2000	**28.07759627**
6	4000	750	2500	**370**	0.55	250	0.5	2000	**29.68203034**
7	4000	750	2500	**400**	0.55	250	0.5	2000	**32.08868145**
8	4000	750	2500	**450**	0.55	250	0.5	2000	**36.09976663**
9	4000	750	2500	**500**	0.55	250	0.5	2000	**40.11085181**
10	4000	750	2500	**700**	0.55	250	0.5	2000	**56.15519253**



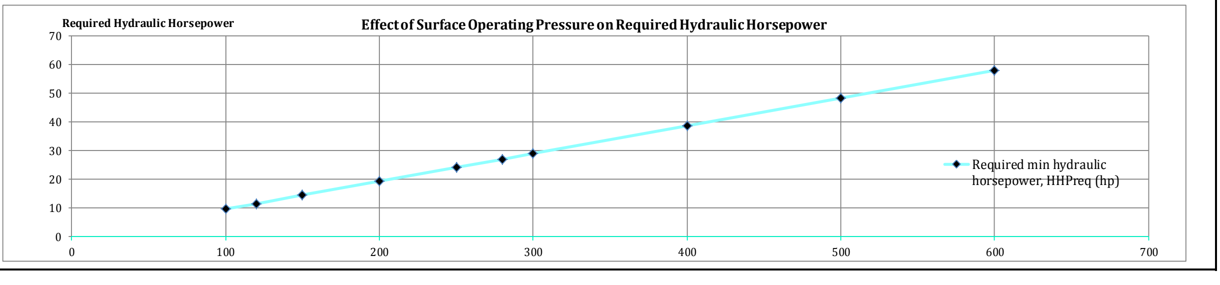
Effect of Pump Efficiency (η)

Set	Fixed Variables				Controlling Variable	Fixed Variables	Resulting Variables		
	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	**Pump Efficiency, η**	Required surface operating pressure (psi)	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	**Required min hydraulic horsepower, HHPreq (hp)**
1	4000	750	2500	300	**0.10**	250	0.5	2000	**4.375729288**
2	4000	750	2500	300	**0.15**	250	0.5	2000	**6.563593932**
3	4000	750	2500	300	**0.20**	250	0.5	2000	**8.751458576**
4	4000	750	2500	300	**0.25**	250	0.5	2000	**10.93932322**
5	4000	750	2500	300	**0.30**	250	0.5	2000	**13.12718786**
6	4000	750	2500	300	**0.35**	250	0.5	2000	**15.31505251**
7	4000	750	2500	300	**0.40**	250	0.5	2000	**17.50291715**
8	4000	750	2500	300	**0.50**	250	0.5	2000	**21.87864644**
9	4000	750	2500	300	**0.55**	250	0.5	2000	**24.06651109**
10	4000	750	2500	300	**0.80**	250	0.5	2000	**35.00583431**



Effect of Surface Operating Pressure

Set	Fixed Variables					Controlling Variable	Resulting Variables		
	Reservoir pressure, pbar (psi)	Desired production rate, qLd (stb/day)	Required producing pressure, pwf (psi)	Power fluid rate, q_{pf} (bbl/day)	Pump Efficiency, η	**Required surface operating pressure (psi)**	Desired productivity index, J (stb/d.psi)	AOF, qmax (stb/day)	**Required min hydraulic horsepower, HHPreq (hp)**
1	4000	750	2500	300	0.55	**100**	0.5	2000	**9.626604434**
2	4000	750	2500	300	0.55	**120**	0.5	2000	**11.55192532**
3	4000	750	2500	300	0.55	**150**	0.5	2000	**14.43990665**
4	4000	750	2500	300	0.55	**200**	0.5	2000	**19.25320887**
5	4000	750	2500	300	0.55	**250**	0.5	2000	**24.06651109**
6	4000	750	2500	300	0.55	**280**	0.5	2000	**26.95449242**
7	4000	750	2500	300	0.55	**300**	0.5	2000	**28.8798133**
8	4000	750	2500	300	0.55	**400**	0.5	2000	**38.50641774**
9	4000	750	2500	300	0.55	**500**	0.5	2000	**48.13302217**
10	4000	750	2500	300	0.55	**600**	0.5	2000	**57.7596266**



Sensitivity Study [Economic Analysis]

Originally developed by Lye Yan Ching

This sensitivity analysis only involves economic parameters which affect the nett profit and economic viability (conclusion).
For economic parameters, please proceed to **Technical Sensitivity Study.**

Part 1 - Economic Analysis (for Hydraulic Pumps & Gas Lift System)

Assumptions			
Initial Production Rate:	1250 mcf/D	Gas Price ($): $	8.46 / M cf
Lifetime of the Machinery:	8 Years	Inflation Rate:	4.50% per year
Annual Repair Cost:	$ 36,000.00 / year		
Machine Failure Repair Cost:	$ 48,000.00 / time/year		

Effect of Installation Cost

Set	Controlling Variable: Installation Cost ($)	Fixed Variables: Increment in Production (MMscfd)	Fixed Variables: Fuel/ Power Consumption ($/month)	Fixed Variables: Repair & Failure Cost ($/month)	Resulting Variables: Profit ($/month)	Resulting Variables: Viability
1	$ 100,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
2	$ 120,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
3	$ 150,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
4	$ 200,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
5	$ 250,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
6	$ 300,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
7	$ 350,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
8	$ 400,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
9	$ 500,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY VIABLE
10	$ 600,000.00	2.5	$ 85,000.00	$ 7,000.00	$ 542,500.00	ECONOMICALLY NOT VIABLE

Effect of Production Increment

Set	Fixed Variables: Installation Cost ($)	Controlling Variable: Increment in Production (MMscfd)	Fixed Variables: Fuel/ Power Consumption ($/month)	Fixed Variables: Repair & Failure Cost ($/month)	Resulting Variables: Profit ($/month)	Resulting Variables: Viability
1	$ 100,000.00	1.0	$ 85,000.00	$ 7,000.00	$ (32,000.00)	ECONOMICALLY NOT VIABLE
2	$ 100,000.00	1.5	$ 85,000.00	$ 7,000.00	$ (2,000.00)	ECONOMICALLY NOT VIABLE
3	$ 100,000.00	2.0	$ 85,000.00	$ 7,000.00	$ 28,000.00	ECONOMICALLY NOT VIABLE
4	$ 100,000.00	3.0	$ 85,000.00	$ 7,000.00	$ 88,000.00	ECONOMICALLY NOT VIABLE
5	$ 100,000.00	3.5	$ 85,000.00	$ 7,000.00	$ 118,000.00	ECONOMICALLY VIABLE
6	$ 100,000.00	3.7	$ 85,000.00	$ 7,000.00	$ 130,000.00	ECONOMICALLY VIABLE
7	$ 100,000.00	4.0	$ 85,000.00	$ 7,000.00	$ 148,000.00	ECONOMICALLY VIABLE
8	$ 100,000.00	4.2	$ 85,000.00	$ 7,000.00	$ 160,000.00	ECONOMICALLY VIABLE
9	$ 100,000.00	4.5	$ 85,000.00	$ 7,000.00	$ 178,000.00	ECONOMICALLY VIABLE
10	$ 100,000.00	6.0	$ 85,000.00	$ 7,000.00	$ 268,000.00	ECONOMICALLY VIABLE

Effect of Power Consumption

Set	Fixed Variables: Installation Cost ($)	Fixed Variables: Increment in Production (MMscfd)	Controlling Variable: Fuel/ Power Consumption ($/month)	Fixed Variables: Repair & Failure Cost ($/month)	Resulting Variables: Profit ($/month)	Resulting Variables: Viability
1	$ 100,000.00	4.5	$ 50,000.00	$ 7,000.00	$ 213,000.00	ECONOMICALLY VIABLE
2	$ 100,000.00	4.5	$ 60,000.00	$ 7,000.00	$ 203,000.00	ECONOMICALLY VIABLE
3	$ 100,000.00	4.5	$ 70,000.00	$ 7,000.00	$ 193,000.00	ECONOMICALLY VIABLE
4	$ 100,000.00	4.5	$ 80,000.00	$ 7,000.00	$ 183,000.00	ECONOMICALLY VIABLE
5	$ 100,000.00	4.5	$ 85,000.00	$ 7,000.00	$ 178,000.00	ECONOMICALLY VIABLE
6	$ 100,000.00	4.5	$ 95,000.00	$ 7,000.00	$ 168,000.00	ECONOMICALLY VIABLE
7	$ 100,000.00	4.5	$ 100,000.00	$ 7,000.00	$ 163,000.00	ECONOMICALLY VIABLE
8	$ 100,000.00	4.5	$ 200,000.00	$ 7,000.00	$ 63,000.00	ECONOMICALLY NOT VIABLE
9	$ 100,000.00	4.5	$ 250,000.00	$ 7,000.00	$ 13,000.00	ECONOMICALLY NOT VIABLE
10	$ 100,000.00	4.5	$ 300,000.00	$ 7,000.00	$ (37,000.00)	ECONOMICALLY NOT VIABLE

Effect of Power Consumption

Set	Fixed Variables: Installation Cost ($)	Fixed Variables: Increment in Production (MMscfd)	Fixed Variables: Fuel/ Power Consumption ($/month)	Controlling Variable: Repair & Failure Cost ($/month)	Resulting Variables: Profit ($/month)	Resulting Variables: Viability
1	$ 100,000.00	4.5	$ 30,000.00	$ 5,000.00	$ 235,000.00	ECONOMICALLY VIABLE
2	$ 100,000.00	4.5	$ 30,000.00	$ 10,000.00	$ 230,000.00	ECONOMICALLY VIABLE
3	$ 100,000.00	4.5	$ 30,000.00	$ 20,000.00	$ 220,000.00	ECONOMICALLY VIABLE
4	$ 100,000.00	4.5	$ 30,000.00	$ 40,000.00	$ 200,000.00	ECONOMICALLY VIABLE
5	$ 100,000.00	4.5	$ 30,000.00	$ 60,000.00	$ 180,000.00	ECONOMICALLY VIABLE
6	$ 100,000.00	4.5	$ 30,000.00	$ 80,000.00	$ 160,000.00	ECONOMICALLY VIABLE
7	$ 100,000.00	4.5	$ 30,000.00	$ 80,000.00	$ 160,000.00	ECONOMICALLY VIABLE
8	$ 100,000.00	4.5	$ 30,000.00	$ 90,000.00	$ 150,000.00	ECONOMICALLY VIABLE
9	$ 100,000.00	4.5	$ 30,000.00	$ 100,000.00	$ 140,000.00	ECONOMICALLY VIABLE
10	$ 100,000.00	4.5	$ 30,000.00	$ 200,000.00	$ 40,000.00	ECONOMICALLY NOT VIABLE