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Economic evaluation of the mixed-refrigerant loop of a propane-precooled mixed-refrigerant (C3-MR) natural gas liquefaction plant

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ABSTRACT

This study evaluates potential economic performance for propane precooled mixed-refrigerant (C3-MR) natural gas liquefaction process in a real baseload, large-scale plant located in Arzew, Algeria. Two alternative mixed-refrigerant processes were investigated and compared in this study, including a base case mixed-refrigerant loop with dual (double) compressor system and an alternative mixed-refrigerant loop with a single compressor system. The evaluation was done based on five economic variables, namely: payout period (POP), net present value (NPV), internal rate of return (IRR), profitability index (PI) and present value ratio (PVR). The results show that the propane precooling cycle with dual compressor system still gives better economic performance since using a single compressor system result in a 7 % reduction of PI compared to their baseline (dual compressor system) values. In addition, results for net present values show a reduction by 20 % when a single compressor mixed-refrigerant systems was deployed, also with the IRR dropping by a certain percentage. Thus, the dual compressor mixed-refrigerant system remains the more promising process.

KEYWORDS;-*LNG, Economic Evaluation, Economic Performance, Propane Precooling, Mixed-Refrigerant, Natural Gas Liquefaction, Baseload LNG Plants.*

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I. INTRODUCTION

Liquefied natural gas (LNG) has been considered the fastest growing supply source for natural gas with an annual growth rate of 4% (Royal Dutch Shell, 2019; Keens, 1980)). Thus, the industry expects 40% of the energy demand growth between 2019 and 2035 to come from natural gas. Among the various LNG proprietary technologies, a propane precooled mixed-refrigerant (C3-MR) natural gas liquefaction process is considered most suitable for a large baseload LNG plant because of its competitive advantages in terms of flexibility, simplicity, procurement convenience, popularity and strong mobility (Waqar et al, 2022; Farmy et al, 2016; Wang et al, 2016).

A lot of technical evaluation research efforts has gone into improving the energy efficiency and performance of the propane precooled mixed refrigerant system (Okafor et al, 2023; Farmy et al, 2016; Wang et al, 2016). However, focusing on only technical evaluation of this process is not sufficient. Investigating the economics of alternative processes could provide beneficial insight into the efficiency and profitability of this process, which can be useful towards a successful plant and/or project optimization (Gao et al, 2022; Zhang et al, 2020; Wang et al, 2014; Castillo and Dorao, 2010; Bowen et al, 2008; Aspelund et al, 2010). Remeljej and Hoadley (2006) evaluated propane liquefaction processes. Their result analysis showed this process was the most efficient with the lowest total shaft work requirements. Mortazavi et al. (2010) improved the energy efficiency of a propane precooled mixed refrigerant process by absorption chillers and this improvement reduced energy consumption by 21%. However, they did not evaluate the economics of this process.

Rodgers et al. (2012) evaluated a propane precooled mixed refrigerant process enhanced by three types of waste heat driven absorption chillers, with their results showing that the required waste heat for absorption chillers could be recovered from a single gas turbine, and the coefficient of performance (COP) and cooling capacity were increased by 13% and 23%, respectively. However, the above research efforts all focus on the technical evaluation of the processes, including the wok of Okafor et al (2023), who technically evaluated the performance of an alternative mixed refrigerant process of a real propane precooled mixed refrigerant LNG plant in Algeria. Despite improving the COP and specific power of this facility, they avoided studying the economics of the process. Thus, the economic performance for adopting a propane precooling cycle is still, in certain aspects, unclear.

This paper aims to fill this gap by studying and evaluating the economic performance of propane precooled liquefaction process using a typical baseload LNG facility as presented in Okafor et al (2023), in which they investigated two alternative mixed-refrigerant processes, namely: 1) use of a dual mixed refrigerant compressor (base case); and 2) use of a single mixed refrigerant compressor. The alternative processes were first simulated and optimized in a proprietary steady-state process simulator (Aspen, 2008; Fahmy et al, 2016; Wang et al, 2014; Zhang et al, 2020; Okafor et al, 2023). The economic evaluation of the propane-based processes was done using the crystal ball evaluator (Charnes, 2012; M. Harris, 2015).

II. PROCESS DESCRIPTION AND METHODOLOGY

Based on technical improvement options investigated by Okafor et al (2023) for propane precooled mixed-refrigerant process, alternative mixed-refrigerant loops are investigated to establish the economic performance. The description of the process facility is shown in Figure 1. Figure 1 mimics a real baseloadLNG production plant in Arzew (Algeria). This liquefaction plant uses the Propane Precooled Mixed Refrigerant Technology (C3-MR). For the process of natural gas liquefaction to be completed, the gas has to pass through three zones, namely: (1) The pre-cooling zone; (2) The liquefaction zone, and (3) The subcooling zone. In the precooling zone, propane is used to precool both the natural gas and the mixed refrigerant. The propane is compressed by a propane compressor to high temperature and pressure (about 116^{o}C and 20bar, respectively). The compressed propane is cooled to about 15^{o}C in a condenser and sent to a propane surge tank. It is then passed through J-T valves (this throttling process drops the temperature and pressure to approx. 5^{o}C and 5 bar, respectively) and then into the evaporators (starting from the high-pressure evaporator through the medium pressure, and then to the low-pressure evaporator), where they help in precooling the natural gas and the mixed refrigerant. The vapour generated from the evaporators are returned to the propane compressor for compression, as the precooled feedgas drops to -40^{o}C.

In the liquefaction and subcooling zones, a mixed-refrigerant (loop) is used. The mixed refrigerant is selected so that the cooling curve of the natural gas closely matches the heating curve of the refrigerant for maximum thermodynamic efficiency (Okafor et al, 2023). Depending on the composition of the natural gas and the compressor power requirement, the mixed refrigerant could contain the following components, namely: methane, ethane, propane, butane and nitrogen. The case study liquefaction plant investigated in this work is designed with two mixed refrigerant compressors which handles the vapour generated from the liquefaction and subcooling that occurred within the warm and cold bundle sections of the main cryogenic heat exchanger (MCHE). This mixed refrigerant compressor compresses the vapour and passes it through the three stage evaporators, before it enters the mixed refrigerant separator where the mixed refrigerant is split into both light and heavy ends. The heavy end undergoes further cooling (first to about -98^{o}C and then to about -119^{o}C after throttling) in the warm bundle of the MCHE, where some throttling occurs, causing a J-T valve to expand the fluid which partially flashes with accompanying temperature drop.

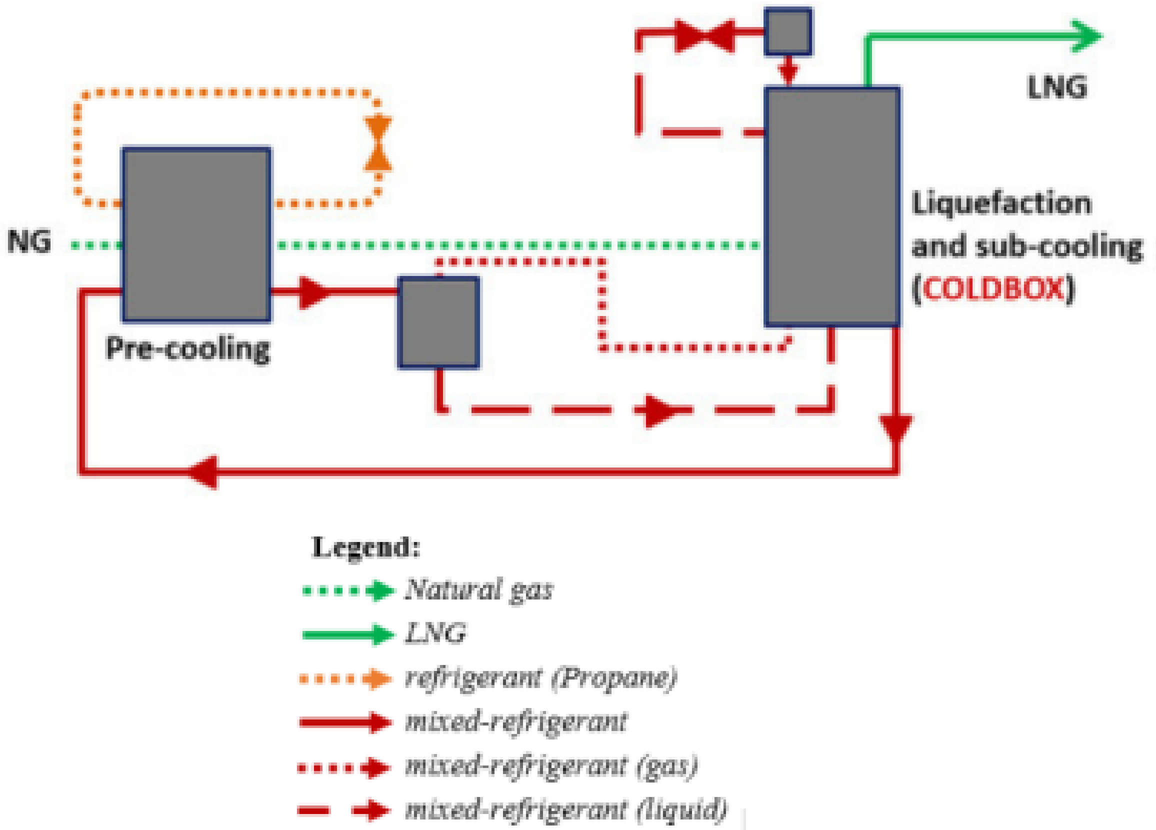

Fig.1: Schematic of the baseload LNG plant in Algeria (Okafor et al, 2023).

The fluid is then sprayed through the spherical wound heat exchangers, providing cooling for the light end of the mixed refrigerant and the natural gas in the warm bundle section of the MCHE. Essentially, the heavy end of the mixed refrigerant is used to produce chilling and liquefaction in the warm bundle of the MCHE before returning to the first stage of the MR compressor for compression. The light end of the MR passes successively through the warm and cold bundle of the MCHE where it is cooled to -158 degree Celsius. It is then made to pass through a J-T valve which further drops its temperature to below its liquefaction temperature. It is then used to chill the cold bundle of the MCHE, causing the natural gas to sub-cool (subcooling zone). The natural gas is then taken to the LNG storage, ready for export. Table 1 shows the MR composition.

Table 1: Mixed Refrigerant (MR) Composition.

	Mole Fractions
Methane	0.5000
Ethane	0.2000
Propane	0.1500
i-Butane	0.0000
n-Butane	0.0000
Nitrogen	0.1500
H2O	0.0000

Our methodology for this study involved the use of proprietary simulators (Harris, 2015; Aspen, 2008). The case study LNG plant was modelled using a steady state simulator (Aspen, 2008) where the economic evaluation tool within this simulator was deployed. Thereafter, a stochastic software for financial forecasting and modelling – the crystal ball (Harris, 2015), was employed, with results emanating from the work plotted in excel. We simulated the production profile for the different process conditions, assuming a theoretical gas market price which is in consonance with what is currently obtainable in the market. Since natural gas prices are not constant, LNG prices were triangulated in crystal ball using the upper and lower limits of LNG prices for the past two (2) years as our minimum and maximum values, and the mean gas price as the base case. The modelling in the proprietary simulator involve the use of real data from local gas fields. A lot of steps are followed in the model simulation including steps that determined the number of operating years, project title, project lifespan, operational hours, plant start-up length following construction, start of basic engineering, hourly operational year (8760hrs), economic evaluation and spreadsheet output. The steps for the crystal ball analysis involves the design of the deterministic model aiming to compute the required economic variables, namely: (1) Net Present Value (NPV): (2) Internal Rate of Return (IRR); (3) Profitability Index (PI): (4) Present Value Ratio (PVR) and (5) Pay Out Period (POP). Other necessary steps for the crystal ball study include the exporting of the crystal ball dataset into an excel sheet, defining the assumptions and forecast variables and running the simulation.

III. RESULTS AND DISCUSSION

Pay out period (POP)

To analyze the economic performance of the alternative mixed-refrigerant loops used in the case study **(Okafor et al, 2023),** the two mixed-refrigerant loops were considered in relation with the required economic variables, one of which is the pay out period (POP). In respect of the POP, Figures 2 and 3 show the results of the cumulative cashflow versus the life of the LNG project (in years) for the simulated single mixed-refrigerant compressor system and the dual mixed-refrigerant (MR) compressor system of the LNG plant, respectively. Both figures show that the two alternative process configurations have the same pay out period of seven (7) years. The dual MR process has a higher capital and operating cost. However, the increased capital and operating costs are offset by the increased productivity due to the higher compression power. But note that this POP could be altered by the pricing dynamics of LNG during the period under consideration. An increase in LNG above the average value for the period will mean that the dual MR compressor LNG plant will have a shorter POP than that of the single MR compressor plant. The reverse will be the case if the LNG price falls below the forecasted amount for the period under price consideration. Hence, the market forces have a big influence on the POP of the baseload LNG plant.

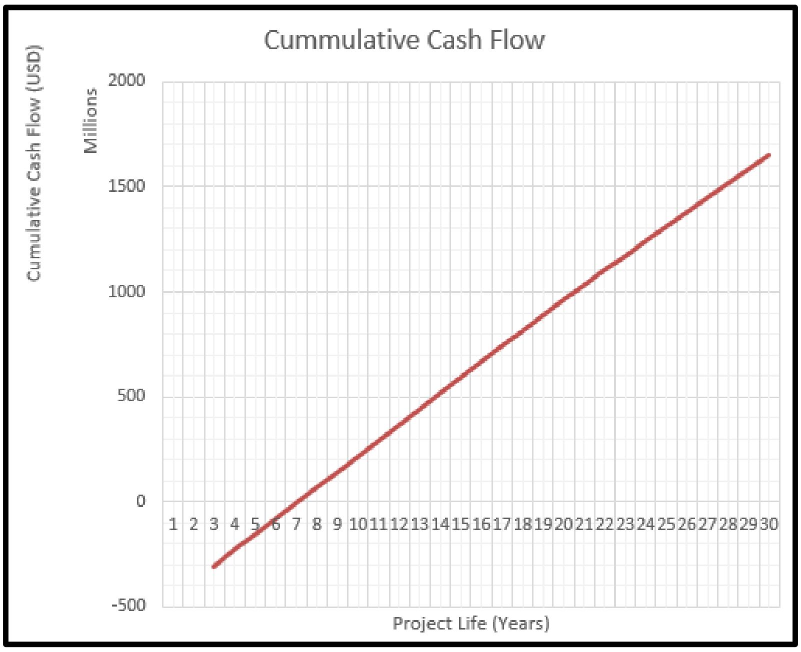

Figure 2: Cash Flow Diagram for Single MR Compressor C3-MR LNG Plant.

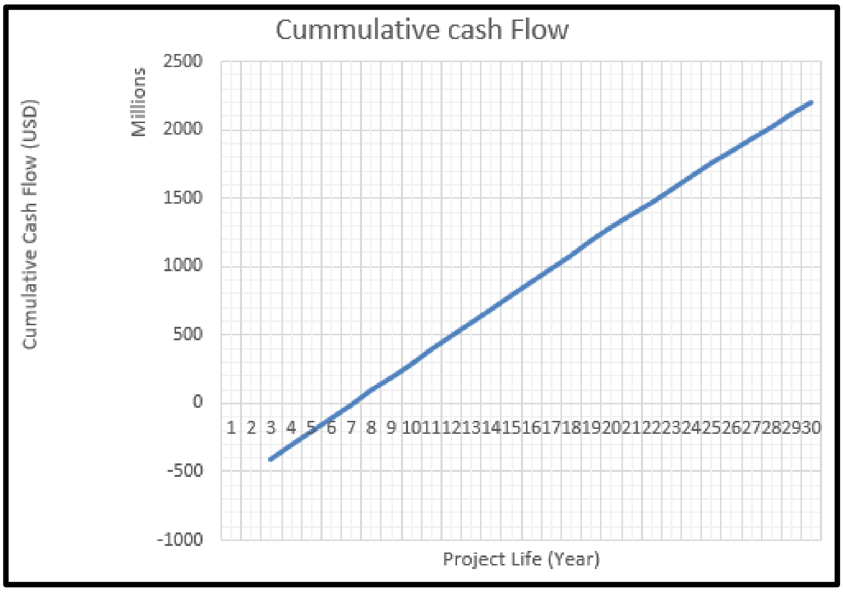

Figure 3: Cash Flow Diagrams for Dual MR Compressor C3-MR LNG Plant.

Net present value (NPV)

Figures 4 and 5 compare the NPVs of the single MR compressor LNG plant with that of the dual MR compressor LNG plant. The results show a base case NPV of $111,751,538.88, a median NPV of $104,392,062,01, a minimum NPV of $27,205,412.45, and a maximum NPV of $175,888,621.45 within a 90% confidence interval for the dual compressor C3-MR plant,

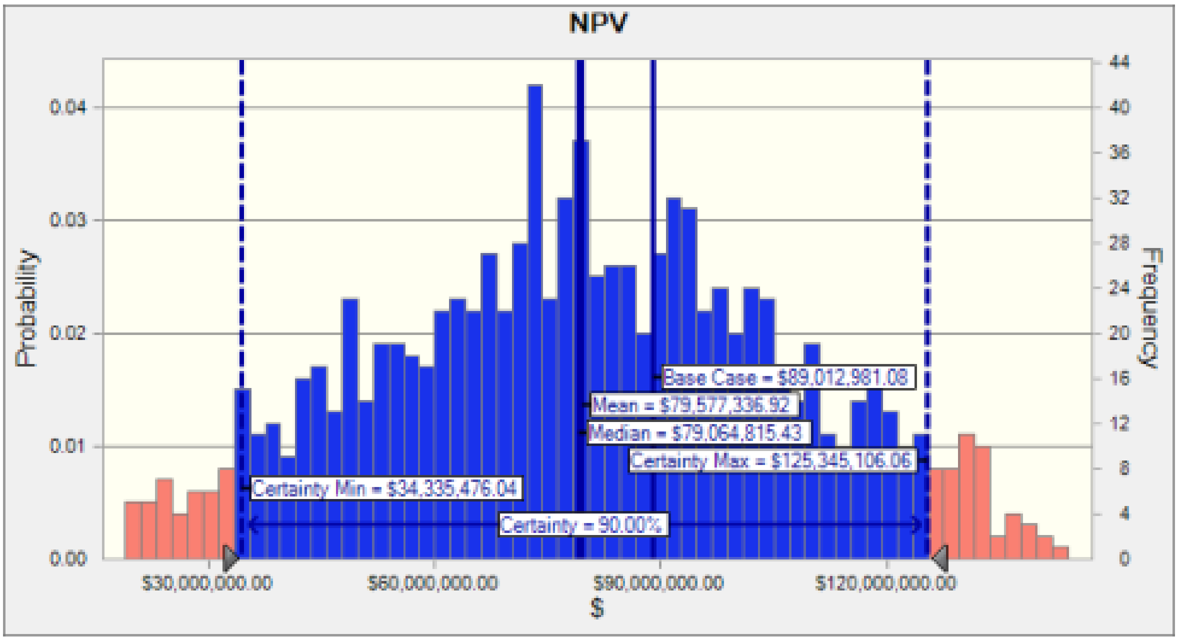

Fig 4: NPV for the single MR compressor C3-MR LNG plant.

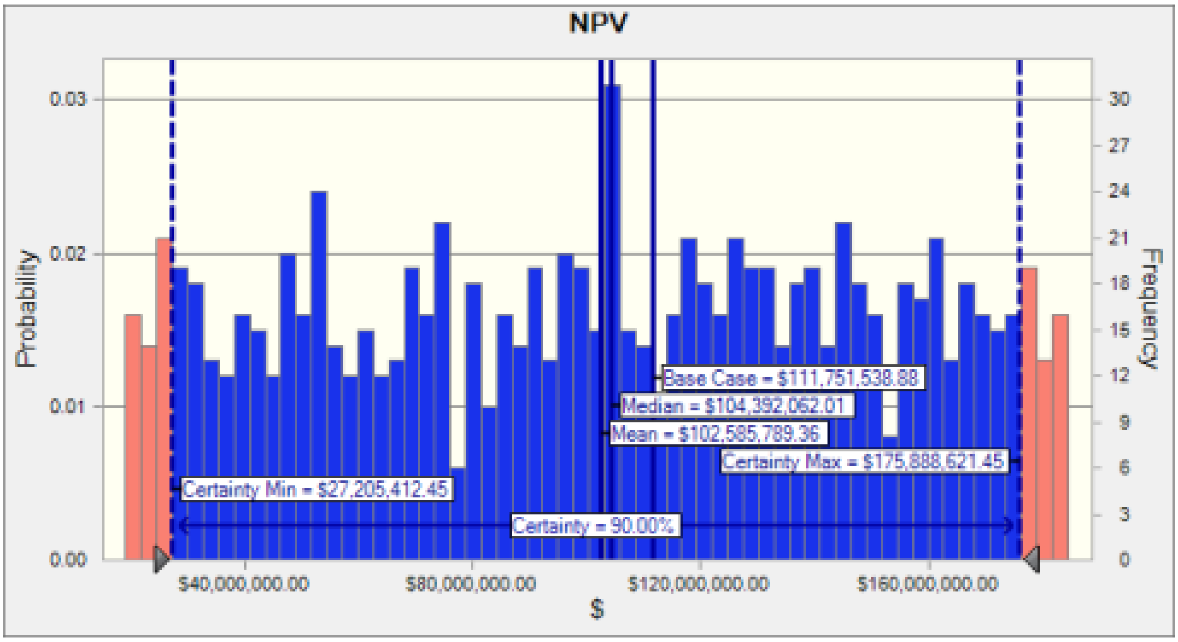

Fig. 5: NPV for dual MR Compressor C3-MR LNG Plant.

respectively. This is evidently higher than that of the single compressor C3-MR plant with a base NPV of 89,012,981.08. The NPV values for the two scenarios clearly show that the dual compressor C3-MR plant will yield better returns on investment per capita over the single compressor C3-MR LNG liquefaction plant.

Internal Rate of Return (IRR)

The internal rate of return (IRR) of a capital project is the discount factor of the project for which the NPV is zero. It is a critical tool used in investment decision making. The IRR for the two C3-MR case scenarios are presented in Figures 6 and 7. As shown from both figures, the

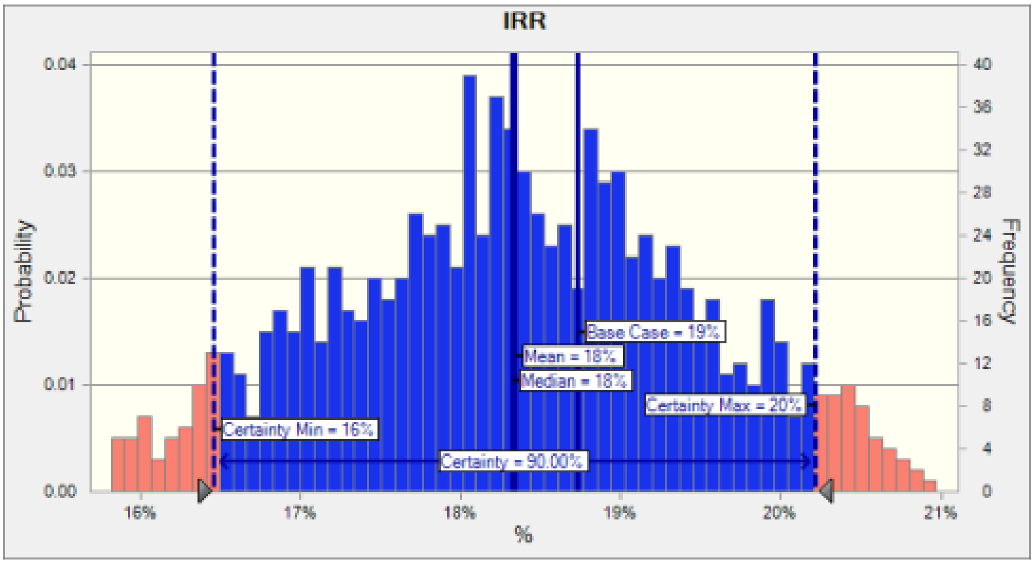

Fig. 6: IRR for Single Compressor C3-MR LNG Plant.

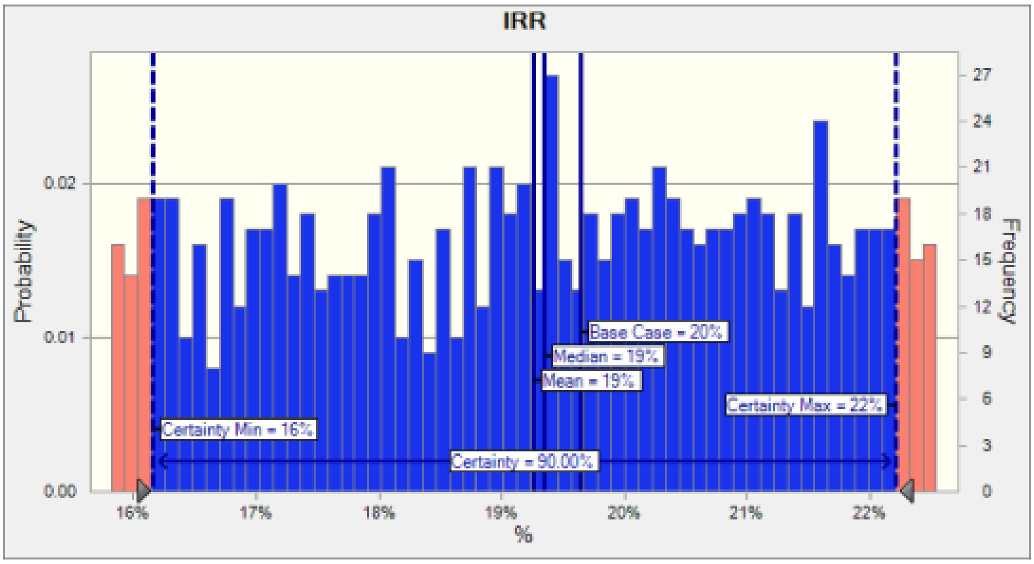

Fig. 7: IRR for Dual Compressor in C3-MR LNG Plant.

dual compressor system yielded a marginal higher rate of return. A base IRR of 20%, maximum and minimum value of 16% and 22%, and a median and mean IRR of 19% with 95% confidence interval. The single compressor C3-MR case yielded a base IRR of 19%, a mean and median value of 18%, and a maximum IRR of 20%, with a 95% confidence level. Both cases have a 90% certainty level. The dual C3-MR LNG plant again is the preferred design as its IRR is higher than that of the single compressor.

Profitability Index (PI)

Profitability Index (PI) is another tool for investment decision making and some results based on this variable are presented in figures 8 and 9. It is also known as the profit investment ratio (PIR) and is used to rank competing capital projects to know which is likely to be the most

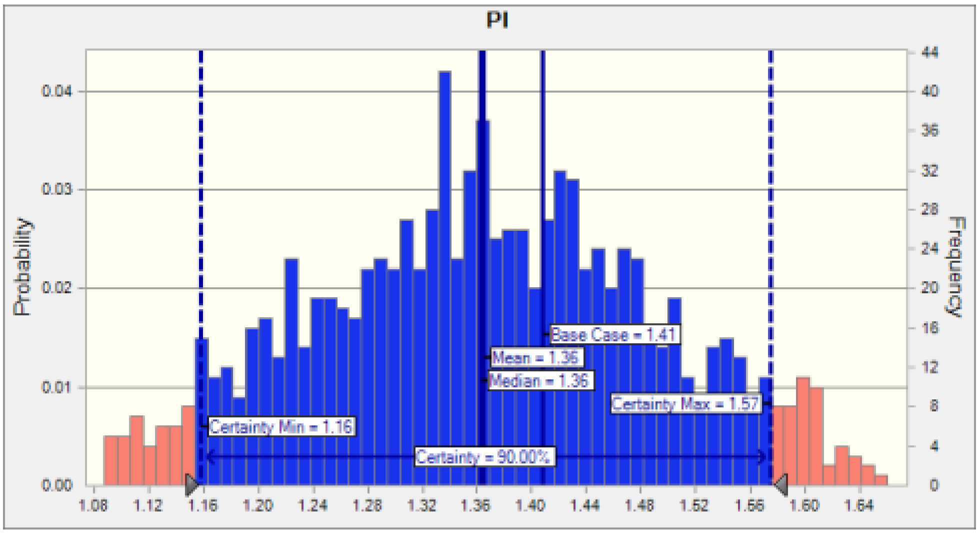

Fig.8: PI of Single Compressor C3-MR LNG Plant.

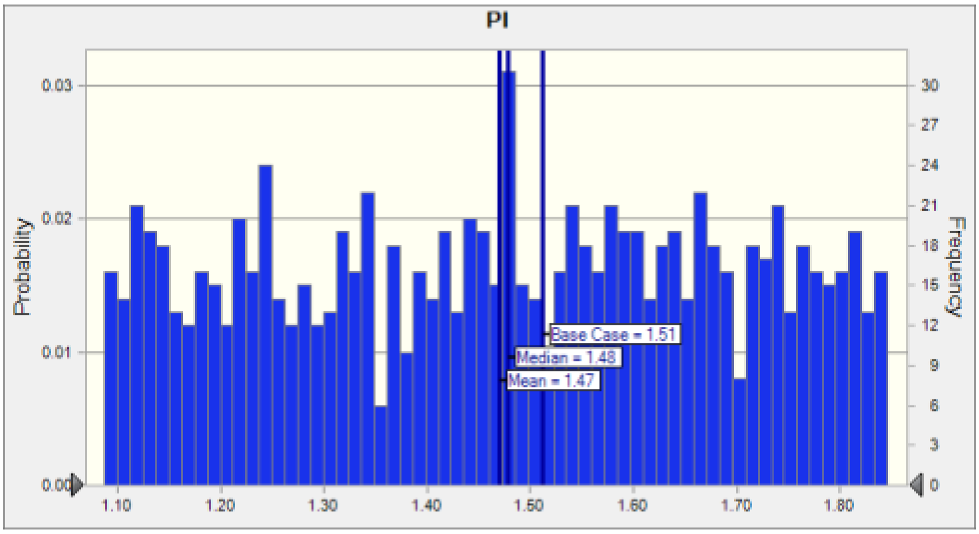

Fig.9: PI of Dual Compressor C3-MR LNG Plant.

profitable. It is gotten by dividing the present value of future cash flow by the capital investment. A Positive PI shows the investment is profitable. When there are a number of alternative capital projects to invest in, the project with the highest PI is the most profitable. The PI values of the single and double compressor C3-MR plant was also calculated (see Figures 8 and 9). From both figures, we can observe that the dual compressor system has a base case PI of 1.51 while the single compressor system has a base case PI of 1.41. Hence, the dual compressor MR system will yield greater profit on investment**.**

Present value ratio (PVR)

The PVR is defined as the net present value divided by the net negative cash outflows. It measures the net present value of an investment per unit investment. The PVR of an investment can be zero, negative or positive. If PVR is zero, it means we are at breakeven point. If PVR is negative, the project isn't profitable. If it is positive, the project is profitable and satisfactory. The PVRs for the two-case study LNG plant are shown in Figures 10 and 11. The PVR of the

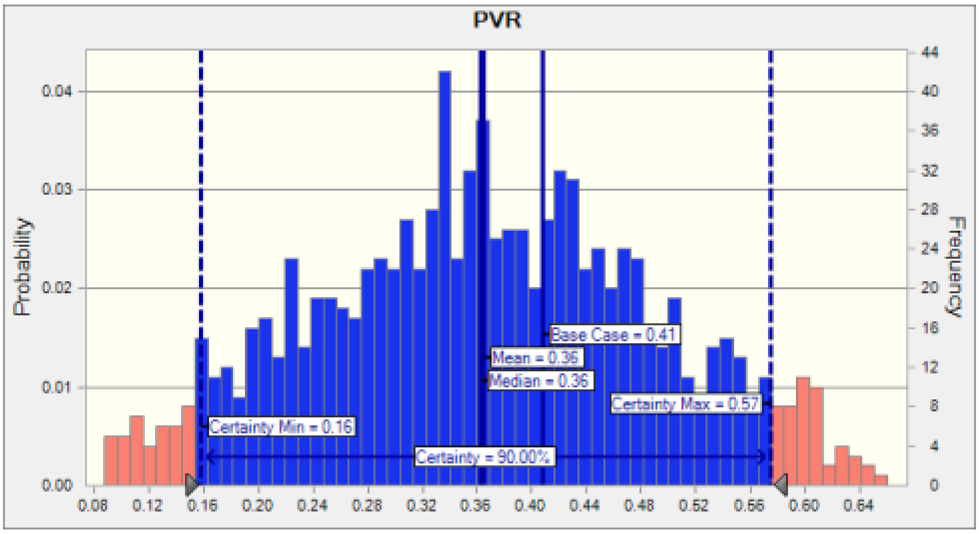

Fig.10: PVR for the Single Compressor C3-MR LNG Plant.

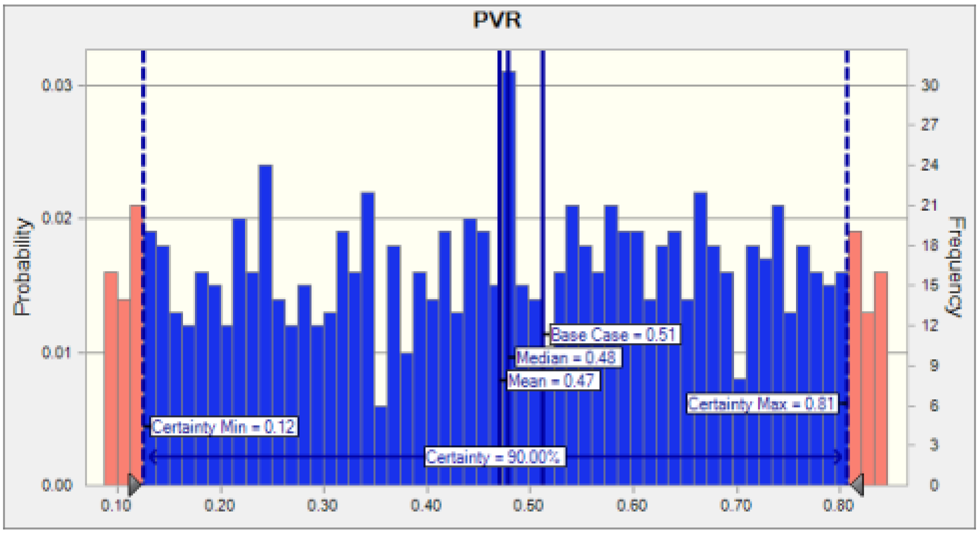

Fig.11: PVR for the Dual Compressor C3-MR LNG Plant.

Dual Compressor C3-MR System is 0.51 while that for the single Compressor C3-MR System is 0.41. This shows both are satisfactorily profitable investment decisions. However, the dual compressor C3-MR system will be a better alternative because of its higher PVR value. Table 2 lists the different measures of profitability and what they indicate as to the LNG simulation cases.

Table 2: Parameters for Economic Evaluation of C3-MR LNG Plant

Column1	Column2	Column3	Column4
Parameters	**Single Compressor**	**Dual Compressor**	**Decision**
Pay Out Period	**7years**	**7years**	**Not Clear**
Internal Rate of Return	**19%**	**20%**	**Dual**
Net Present Value	**$89,012,981.08**	**$111,751,538.88**	**Dual**
Profitability Index	**1.41**	**1.51**	**Dual**
Present Value Ratio	**0.41**	**0.51**	**Dual**

IV. CONCLUSION

The economic performance of a large-scale, baseload LNG plant was determined in this study. A conventional propane precooled mixed refrigerant process, both with single and dual mixed-refrigerant compressor, were economically evaluated. Five different economic performance variables were investigated, namely pay out period, net present value, internal rate of return, profitability index and present value ratio. It is evident from the results that using two compressors in the mixed refrigerant loop lead to increased productivity in the C3-MR LNG plant. Although the increased compression power means more energy utilization, and thus increased capital and operating cost, the increase in productivity more than compensates for these extra costs. Table 2 summarizes that the dual compressor C3-MR system outperforms the single compressor C3-MR system. Apart from the pay-out period which is the same for both system (7years), the dual compressor LNG plant performed better in every other economic evaluation index. In the long run, the higher NPV of the dual compressor will mean more cash inflow for every capital investment. However, it is important to note that this can be affected by the fluctuation in gas price. Hence, if the price of natural gas falls significantly (to about $180/ton), it could lead to a longer pay out period for the dual compressor C3-MR liquefaction plant, thus taking a significantly longer time to break even due to its higher initial capital and operating cost. Overall, the dual compressor mixed refrigerant loop of the propane precooled mixed refrigerant process showed better economic performance relative to the single compressor mixed refrigerant loop.

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