ZR-LNG™ Dual Expander Methane Cycle Liquefaction Technology Applied to FLNG

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Abstract

The Gasconsult ZR-LNG™ liquefaction technology, deploying a patented dual methane expander refrigeration configuration, provides a step change improvement in economics for single train liquefaction capacities up to 2 million tonnes/year of LNG. The process uses the feed natural gas as the refrigerant medium. It requires no external refrigerant inventory and its associated storage, production and transfer systems, reducing both cost and space requirements. This makes the process of special relevance for FLNG applications where the freed up deck space can potentially be utilised for additional productive liquefaction capacity. Energy efficiency is significantly higher than the dual nitrogen expander and single mixed refrigerant systems; approaching that achieved by base load processes. Comparative technical and investment return data is provided for ZR-LNG™ and competing technologies including energy efficiency, carbon emissions, capital costs and project returns as measured by Net Present Value and Internal Rate of Return.

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Introduction

Gasconsult Limited has developed and patented a new LNG liquefaction technology termed ZR-LNG^{TM} (Zero Refrigerant LNG). The technology uses a dual methane expander configuration which combines high energy efficiency, low carbon emissions, low capital cost and low space requirement. It is an advance on existing methane expander cycles deployed on a number of US LNG peaking and gas processing plants and the various nitrogen cycle and single mixed refrigerant (SMR) processes proposed for mid-scale and floating LNG (FLNG).

The ZR-LNG^{TM} process was originally conceived in the mid 2000s with the key objective of developing a simple, low cost and energy efficient mid-scale liquefaction cycle. Extensive engineering development was completed on early FLNG versions of the technology for a nominal 1 million tonne per annum (tpa) modular train. Design development has subsequently seen a reduction in complexity, total elimination of liquid hydrocarbon refrigerants and a reduction in capital cost. A shaft compressor power of close to 300kWh/tonne with 20°C cold box inlet temperature is achieved at a liquefaction unit capital cost for modularised units (excluding gas pre-treatment) in the range $130-150 per annual tonne of capacity. The low power demand is achieved without the complexity of feed gas pre-cooling or other process nuances; providing an intrinsic simplicity to the system. It permits greater LNG production from a given gas turbine driver, substantially enhancing project returns. The lower space requirement potentially adds further advantage in that it may be possible to install more liquefaction capacity on the available deck area; further increasing production and revenues.

Design Perspectives for LNG Liquefaction Technologies

Plant Capacity

Base load LNG production is taking place in ever larger capacity plants. LNG projects typically now comprise multiple streams with single train capacities in the range 4-8 million tpa. These large plants are characterized by a high degree of complexity to maximise energy efficiency, enhance co-product value realisation and improve on-line availability. They carry the knock-on burdens of limited vendor competition for high value equipment, high capital cost and extended project schedules. A further factor for these mega-scale plants is the requirement for a world class gas reserve, possibly in excess of 20 trillion cubic feet (TCF); required to sustain production for up to 25 years.

So-called mid-scale LNG for exploitation of the 1000+ smaller discovered gas fields with reserves of around 1 TCF has been a discussion point for a decade or more. These smaller gas prospects cannot economically sustain the high complexity and capital cost of base load technologies. They require lower capacity and lower capital cost plants to be commercially viable. This is an engineering challenge as economies of scale work against smaller schemes.

Process Technology

The well publicised Shell Prelude FLNG project will employ dual mixed refrigerant (DMR) technology to produce 3.6 million tpa in a single liquefaction train. A further 1.7 million tpa of condensate and LPG will also be recoverable. By its scale of operation and emphasis on energy efficiency Prelude represents the approach of several LNG producers who strive to enhance project returns through higher plant capacities and co-product recovery. However a marked preference has developed amongst some operators for elimination of liquid hydrocarbon refrigerants on FLNG plants. Higher molecular weight hydrocarbons, particularly propane, are extremely hazardous and represent an explosion/fire risk when accumulating in confined spaces. A level of support has thus developed for nitrogen expander processes for FLNG application.

Power consumption for nitrogen cycles is typically 30-60% higher than for mixed refrigerant processes, and the generally larger gas recirculation rates also lead to large line sizes and heavy plant. These factors disadvantage nitrogen cycle schemes, particularly for higher plant capacities. Arguments have been made that the low energy efficiency is affordable with a low cost energy source like stranded gas[1]. However there are compelling arguments for pursuing high process efficiency as lower power demand increases plant capacity, thereby enhancing project Net Present Value (NPV) and Internal Rate of Return (IRR) from equivalent turbine drivers; and also reducing associated CO_2 emissions per unit of LNG production.

ZR-LNG™ Technology

The need to reduce the power demand for an expander based process while preserving the safety and simplicity of the nitrogen cycle led to the development of the ZR-LNG™ process.

Process Scheme

In the ZR-LNG™ process the refrigerant is the feed natural gas. A liquefaction unit net drive shaft power of close to 300 kWh/tonne of LNG with 20°C 'cooled to' temperature is achieved; depending on the feedstock composition, pressure and ambient conditions. This low power demand is achieved without the complexity and cost arising from feed gas pre-cooling and is only marginally inferior to base load schemes. A schematic of the ZR-LNG™ process is shown in Fig 1.

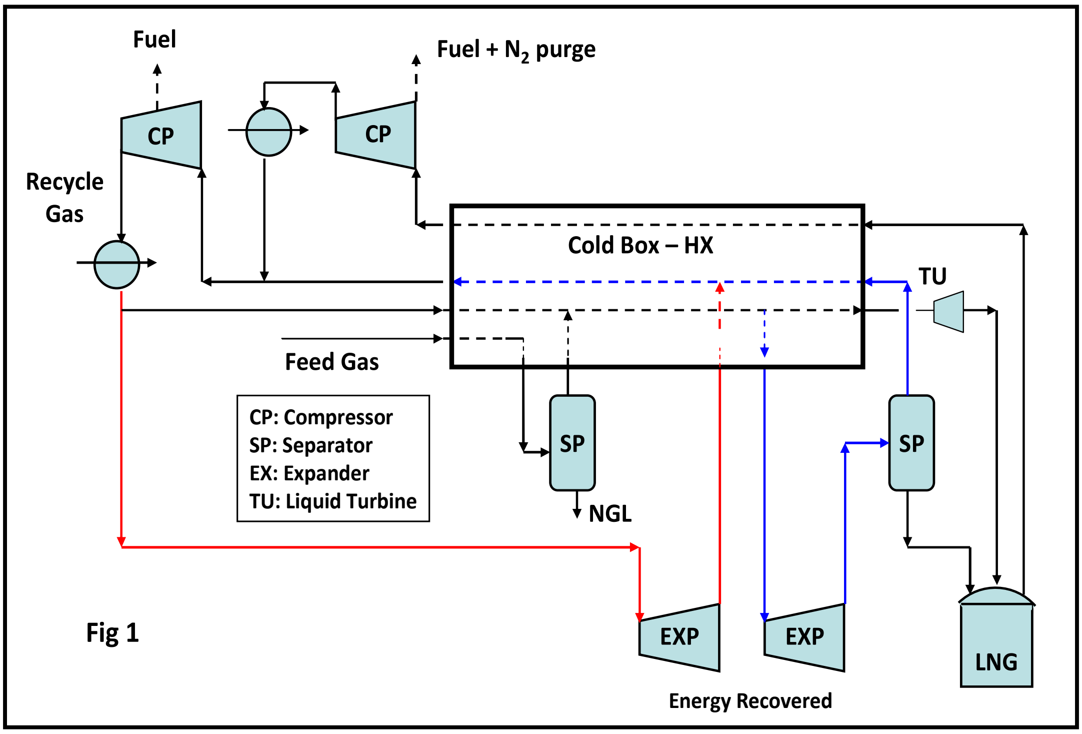

Fig 1

Liquefaction is achieved through the use of two separate expander circuits indicated in red and blue. The low temperature blue circuit expander performs a partial direct liquefaction of its feed. Typically 35% of the compression power requirement to operate the process is recovered through the gas expanders. A further reduction in power demand is effected by an expander-turbine on the liquid product run down to storage.

The technology encapsulates simplicity; a 1 million tpa train comprises only 2 compressor packages plus 8 major equipment items. The cold box can comprise as few as three passages (or four when pre-condensation of natural gas liquids is necessary); and all passages in the heat exchange cores have vapour phase feeds. As the process has no external cryogenic refrigerant cycle and requires no liquid refrigerant storage or nitrogen production/top-up system, several equipment items are eliminated, together with associated bulk materials, fabrication and construction. The focus on simplicity achieves a significant reduction in capital cost and also, importantly, frees up deck space on FLNG facilities.

Two main factors contribute to ZR-LNG^{TM}'s other key attribute; its significantly lower power requirement relative to nitrogen expander processes. The main contributing factor is the higher molar specific heat and lower molar compression power requirement with methane. This results in lower recycle flow rates and attendant lower power demand. A second factor is that liquefaction of part of the feed gas occurs in the liquefying gas expander, converting latent heat directly into mechanical work.

Gasconsult has quantified the benefits of the above factors. Typical dual expander nitrogen cycle configurations were evaluated on the same basis as ZR-LNG^{TM} with respect to ambient conditions, machine efficiencies, pressure drops, and heat exchanger temperature approaches. HYSYS simulations indicate the ZR-LNG^{TM} process can have > 30% lower suction compressor volumes and over 20% lower aggregate machine kW than the dual nitrogen expander schemes.

The combination of low capital cost and high energy efficiency makes ZR-LNG^{TM} highly competitive at single train capacities up to 2 million tpa for both land based and FLNG applications.

Process Flexibility

Simulation work using HYSYS has been carried out on both lean gas feeds and feeds containing up to 7.5% C_2+. The impact of varying gas compositions on process efficiency was found to be limited.

Consideration has also been given to the impact of nitrogen in the feed gas because of its potential to build up in the recycle gas, causing a potential increase in power consumption. Most natural gas feeds contain less than 2% nitrogen. Simulations with up to 5% nitrogen in the feed resulted in an increase in specific power demand of approximately 10%.

As early work was centred on FLNG application of the technology in the North Sea design excursions have also been run to reflect the impact of higher cooling water temperatures typical of the Middle East and Asia. The impact of varying 'cooled to' temperatures is reflected in Fig 2. This shows little difference in impact of this parameter between ZR-LNG^{TM} and typical SMR or nitrogen cycle schemes.

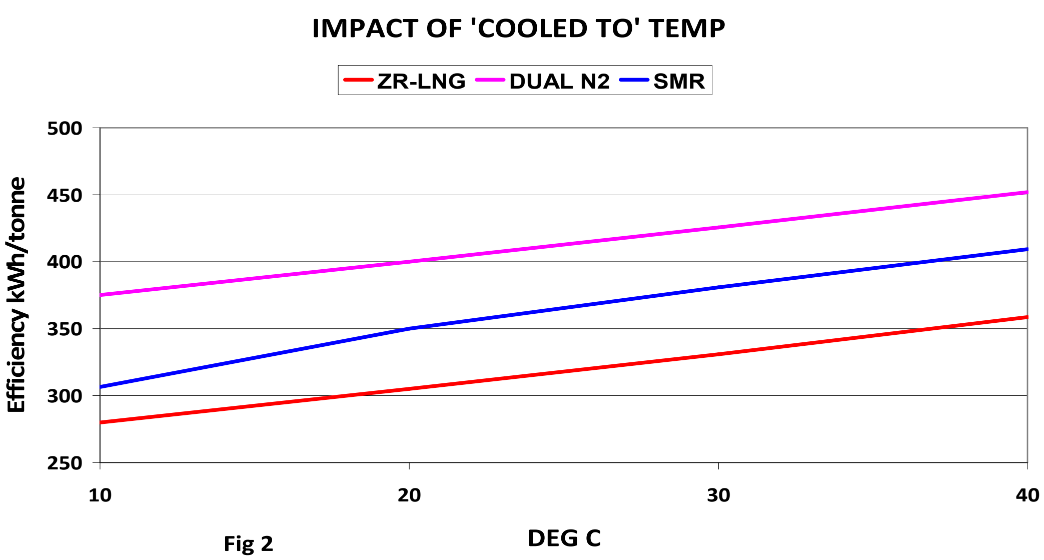

Fig 2

Applicability to FLNG Projects

FLNG schemes draw experience and expertise from conventional onshore LNG plants, LNG shipping/marine facilities and floating production storage and offloading (FPSO) operations, the latter a well established technology for offshore oil recovery. There are many technical challenges in establishing a safe, high availability and viable design for offshore liquefaction, product storage and transfer. A consensus exists that FLNG is technically more challenging than oil applied FPSO. The technical issues include:

- Product containment system and impact of sloshing
- Equipment spacing, plant layout and location of living quarters
- Selection of liquefaction process and inventory/composition of liquid hydrocarbon refrigerant
- Tandem or side-by-side product transfer
- Impact of ship motion on processing operations

It is beyond the scope of this paper to discuss all these issues. However it is well recorded that nitrogen cycle plants have specific advantages in addressing certain safety and operability concerns. Firstly the nitrogen process does not use a liquid hydrocarbon as the refrigerant medium. There is therefore no inventory of high molecular weight liquid hydrocarbons with attendant risk of fire/explosion in the event of leakage. On a floating facility with constrained escape options this is deemed by some operators to be a decisive factor in selecting the liquefaction process. A second factor is that the nitrogen cycle is a single phase process and is unaffected by vessel motions. By contrast, in liquid refrigerant processes, the refrigerant undergoes evaporation in the system heat exchangers, creating a two phase flow which may be motion sensitive.

The ZR-LNG™ process enjoys similar safety and operational benefits as the nitrogen system. Further its refrigerant supply is secure and always assured; and it has superior energy efficiency to both the nitrogen and SMR processes.

From a project return and capital efficiency perspective there is considerable benefit in securing maximum LNG output from the selected gas turbine compressor driver, the normal capacity limiting equipment item for each liquefaction train. It is in this area, arising from its high energy efficiency, that ZR-LNG™ demonstrates a compelling commercial advantage over other mid-scale technologies. All things being equal (e.g. compressor/expander efficiencies and an overall economically matched process equipment configuration) the capacity output from a ZR-LNG™ scheme will realise a higher plant capacity for an equivalent installed compression power than either SMR or dual expander nitrogen schemes. Also the absence of a nitrogen production system or liquid refrigerant handling/storage facilities reduces footprint and weight, potentially freeing deck space for additional liquefaction processing equipment. The higher throughput from lower power demand and additional processing equipment translates into higher cash flows and higher project returns as measured by NPV or IRR.

All the above attributes make the ZR-LNG™ technology particularly well suited to FLNG.

Assessment Data – Nominal 1 Million TPA Scheme

Fig 1 foregoing provides the basic ZR-LNG™ flow scheme applicable to nominal 1 million tpa trains. A recent design exercise based on a GE LM6000PF gas turbine delivering 35.5 MW under site conditions[2] is the basis of the information provided below in Tables 1-4. The Basis of Design applicable to the presented assessment data is as recorded in Table 1.

TABLE 1	**BASIS OF DESIGN**
Gas Composition Mol %:	CH_4 95%; C_2H_6 4%; C_3H_8 1%
Gas Pressure at liquefaction inlet	60 bar
Sea Water/Ambient Air Temperatures	13°C/20°C
Indirect cooling - Sea Water/Circ Water	3°C approach
Process Streams cooled to	20°C
Heat Leak to Cold Box	0.50%
Minimum cryogenic approach temp	3°C
Recycle gas compressor polytropic η	85%
Expander adiabatic η	87%

The related power demands are recorded in Table 2. The power consumption of 306 kWh/tonne is achieved by the process in its basic form; and with no feed gas pre-cooling. Compressor and expander efficiency data was provided from established vendors.

TABLE 2	BASIC OPERATING PARAMETERS
On line factor	345 days per year
LNG product flow rate	131.0 tonnes per hour
Gross recycle compression shaft power	55.9 MW
Expander shaft power recovered to process	20.8 MW
Net recycle compressor shaft power (direct GT drive)	35.1 MW (after 1% gear loss)
Net auxiliaries shaft power	5.0 MW
Net total shaft power	40.1 MW
Net shaft power	306 kWh/tonne LNG

The cost estimate using pre-fabricated liquefaction modules for FLNG application is provided in Table 3. This estimate covers an EPIC work scope and is provided on a 2013 instant execution basis. It relates to the liquefaction unit only and excludes the vessel, feed gas purification, NGL fractionation, utilities, LNG/NGL storage, flare and owners costs.

TABLE 3 – Nominal 1 million tpa train	CAPEX ESTIMATE 2013 US$ Mil
Equipment Supply + Spares	62.8
Bulks Supply	14.8
Installation/Construction/Fabrication	18.9
Transportation	1.9
PLANT TOTAL	**98.4**
Licence Fee/Insurance/Certification	6.0
Project Management/Engineering/Commissioning	28.1
TOTAL ENGINEERING + FEES	**34.1**
CONTINGENCY	**19.9**
TOTAL	**152.4**

Comparison with other Mid-Scale Technologies

ZR-LNG™ was not initially envisaged to compete with large land based base load plants of the type constructed by the oil majors and National Oil Companies. The bench mark technologies were the generic SMR and dual nitrogen expander processes and several commercially promoted variants. Assuming a like for like plant capacity and Basis of Design (Table 1), Table 4 details the comparative power consumptions for the liquefaction units only. The SMR and dual expander nitrogen process data has been secured from literature searches and internal Gasconsult HYSYS simulation work.

TABLE 4 - SYSTEM	LICENSOR/OWNER	ENERGY USE kWhr/TONNE	RELATIVE CO_2 EMISSIONS
ZR-LNG™	Gasconsult	306	0.17kg/kg LNG
Dual N_2 Expander	Several	400	0.21kg/kg LNG
SMR	Several	350	0.18kg/kg LNG

FLNG Case Study

BP recently conducted an internal study on inherently safer FLNG, using individual nitrogen cycle modules based on PGT25+G4 gas turbines, with the intention of eliminating fire and blast risk from the liquefaction section of the topsides. As part of this work BP invited Gasconsult to develop a mass balance for a ZR-LNG^{TM} module based on the same turbine for comparison. BP found that compared to processes based on mixed refrigerant, ZR-LNG^{TM} has the advantage of eliminating LPG refrigerant components as well as their processing and storage. Compared to processes based on nitrogen, ZR-LNG has favourable specific power but may require greater separation gaps for risk management, due to the presence of hydrocarbon leak sources in the congested areas, though this is offset by eliminating the space needed for nitrogen manufacture and storage. Gasconsult used the mass balance prepared for the BP study to generate an internal financial comparison of ZR-LNG^{TM}, dual nitrogen and SMR processes, all based on a 5 train plant. Data for the alternate processes was sourced from the public domain and internal Gasconsult HYSYS simulations.

Design Basis

The design basis for the case study is shown in Table 5 below.

TABLE 5	**PGT25+G4 DRIVER 27.7MW output**
Feed Gas Composition Mol %:	C_1 88.5%; C_2 10.3%; C_3+ <0.1%; N_2 1.1%
Gas Pressure at liquefaction inlet	80 bar
Sea Water Temperature	23°C
Process Streams cooled to	31°C

Financial Analysis

Gasconsult has evaluated the impact of liquefaction process selection by constructing a financial model for an integrated gas field development. This assumes a project financed venture based on the parameters below:

- a debt:equity ratio of 70:30
- loan interest rate of 8%
- discount rate 10%
- loan repayment period 7 years
- depreciation rate 5%
- tax rate 30%
- gas sales price of $10/million BTU
- shipping cost to market $2/million BTU
- interest during construction capitalised
- O&M costs $1/million BTU

Table 6 depicts the relative LNG production from the candidate technologies for 5 train plants with a common feed gas processing system.

TABLE 6 – 5 x Train FLNG	**ZR-LNG^{TM}**	**SMR**	**Dual N_2**
Field Development $ millions	500	500	500
Hull + Topsides $ millions	2390	2390	2390
Base Capex $ millions	2890	2890	2890
Nominal kWh/tonne	329	384	439
Output tpa from 5 x PGT25+G4	3,906,000	3,348,000	2,930,000
Field Life – Years	9	10	12
On-line availability - days/year	345	345	345

Based on the above, project NPVs were calculated for a 2 TCF field. The calculations assume exhaustion of the gas reserve on a constant output basis throughout its life, probably an unlikely occurrence unless later phase inlet compression equipment is installed. However in respect of process comparison the assumption provides a like for like scenario.

The outcome, showing cumulative NPV10 is shown in Fig 3, which has been constructed to illustrate the incremental benefits arising from the relative process efficiencies of the candidate liquefaction technologies. A further point to consider is that the higher capacity ZR-LNG^{TM} scheme earns its full project return as measured by NPV in a shorter time period. For FLNG applications the ZR-LNG^{TM} financial returns would be further advantaged by earlier re-deployment to another stranded gas opportunity.

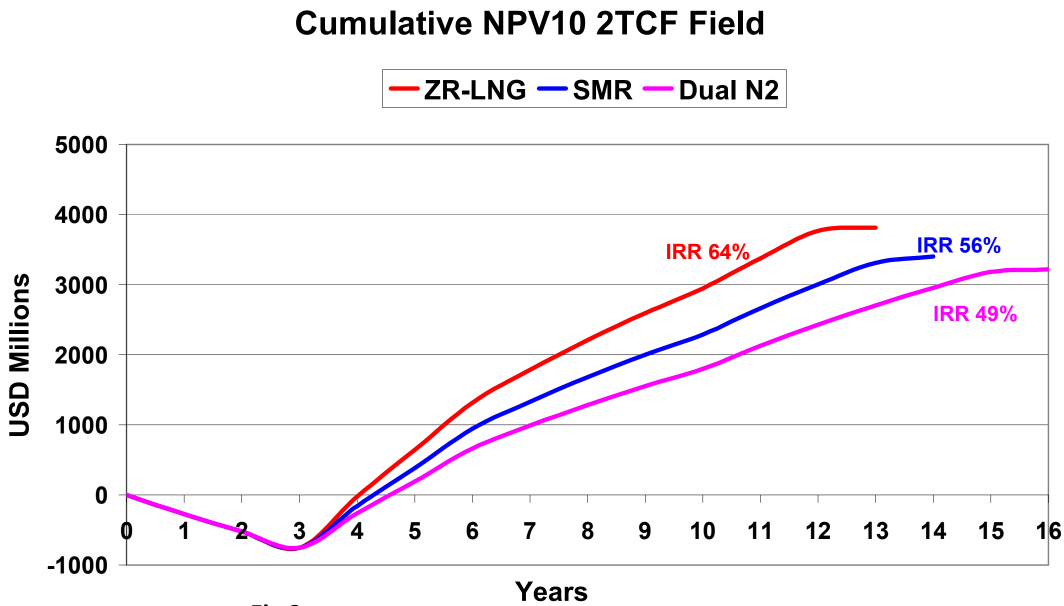

Fig 3

It is clear that process efficiency can be increased at the cost of additional complexity and increased capital (feed gas pre-cooling, use of cold deep seawater cooling etc). Some argue[3] that plant capacity, which drives the financial returns, is a capital cost issue and could be increased by selecting multiple drivers or a driver with more power output (e.g. an LM6000 instead of the PGT25+G4).

Such possibilities would clearly be evaluated at a project’s feasibility phase, along with overall system efficiency. They are beyond the scope of this paper, which aims to evaluate the liquefaction technologies on a level playing field.

In regard to improved efficiency or increased capacity however, these process options are available to the benefit of all the reference technologies and the intrinsically higher efficiency process would always retain its inherent advantage in terms of project financial returns. Further in the case of FLNG applications in particular, physical constraints arising from available deck space may be an inhibiting factor in respect of chasing incremental efficiency or capacity through the use of larger/multiple equipment items or more complex process configurations.

Impact of Capital Cost

Given the relative lack of available data from constructed and commissioned FLNG facilities some considerable uncertainty exists over final installed costs. For the 5 train study presented above Gasconsult investigated the sensitivity of final capital cost; Fig 4 reflects the impact of over-runs on the estimates used in this paper vs. NPV and IRR.

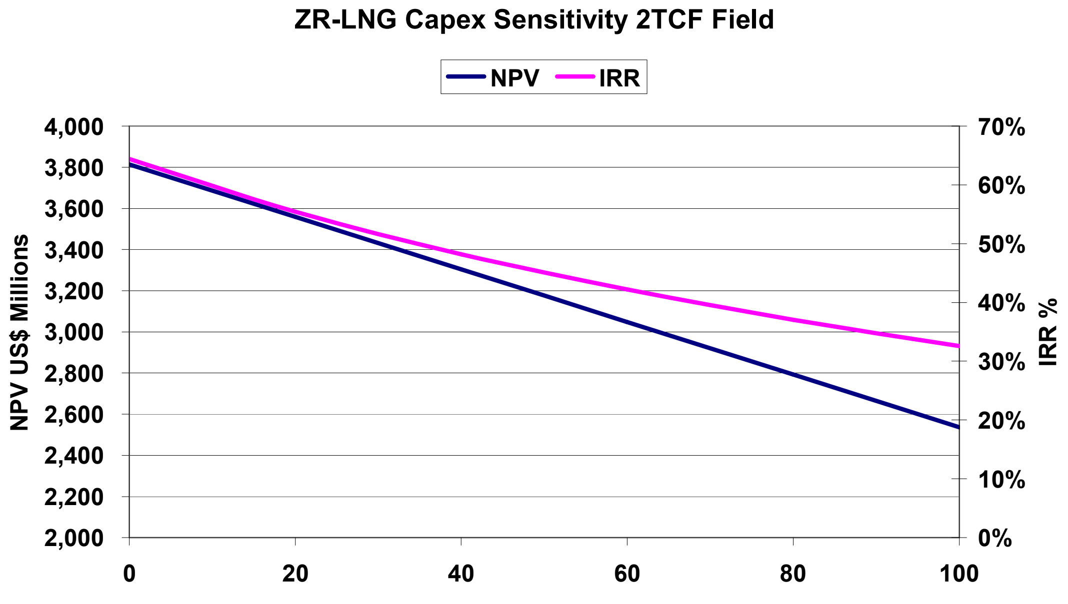

Fig 4

Sensitivity to LNG Price

The sensitivity of the Case Study to variations in the sum received for product LNG is shown in Fig 5.

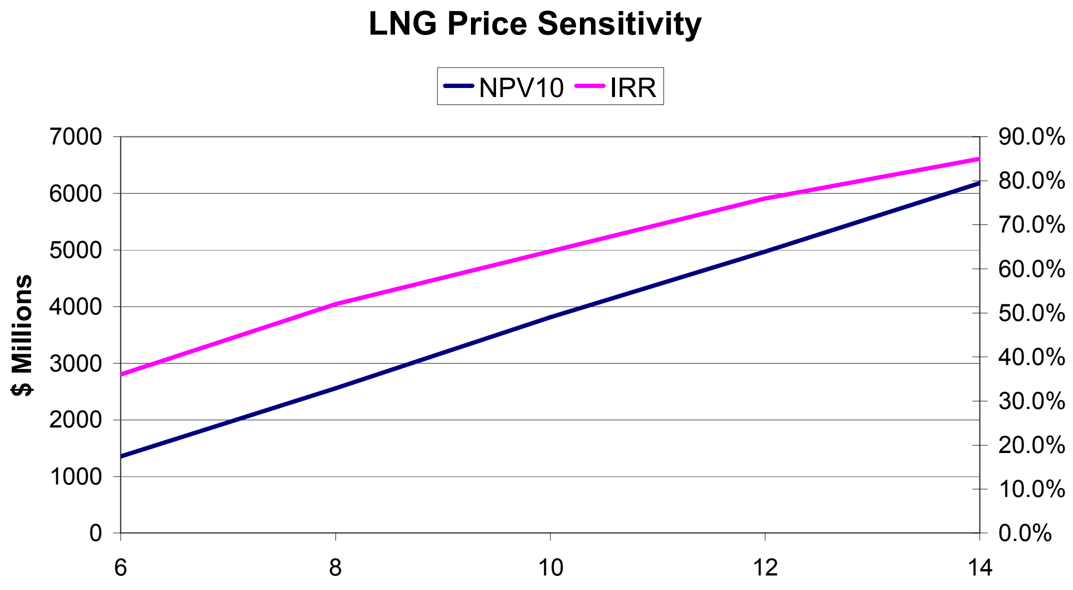

Fig 5

Conclusions

The ZR-LNG^{TM} process is positioned as a simpler, lower capital cost and more energy efficient process than both nitrogen expander cycles and SMR schemes in the mid-scale single train capacity range up to 2 million tpa. The significant reduction in complexity and cost is achieved with a quite limited sacrifice of energy efficiency compared to existing base load plants. The resulting project economics for FLNG schemes appear robust when tested against capital cost and LNG price variations.

Relative to the SMR and nitrogen expander processes ZR-LNG™ represents a step change improvement in project returns when measured on the basis of extracting maximum output from an installed quantum of refrigeration compression power. This technology development, because of its energy efficiency, also repositions expander technology; widening its application envelope to both larger capacity and higher gas cost schemes.

The ZR-LNG™ economic advantages are secured whilst preserving the well established operational benefits of nitrogen cycles for FLNG applications. These include safety through the elimination of liquid hydrocarbon refrigerants, tolerance to ship motion with its impact on multi-phase flows, rapid start-up and reduced flaring.

The technology is also an excellent fit for expansions at existing LNG production facilities looking for a low cost, small footprint and short schedule project to take advantage of an existing surplus of gas processing capacity.

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