OPTIMISATION OF LNG COLD UTILISATION AT A LNG RECEIVING TERMINAL

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN ENERGY TECHNOLOGY

THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT AT KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI

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Topic: Optimisation of LNG Cold Utilisation at a LNG Receiving Terminal

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ABSTRACT

LNG cold energy utilisation technologies, which are techniques that make use of the cold energy from LNG cryogenic temperatures (-163 degree Celsius) during re-gasification process, instead of wasting it into seawater, have been studied. Eleven (11) technologies for LNG cold energy utilisation are identified, i.e. air separation and liquefaction unit, cryogenic power generation, and etc. The technologies were assessed, screened and prioritised by multi-criteria decision making tools, Analytical Hierarchy Process (AHP), technology analysis and strategy concept. Technology Prioritisation Framework is developed to identify the best selected LNG cold energy utilisation technology.

The framework has been applied in a case study at the first LNG (Liquefied Natural Gas) receiving terminal in Thailand. Under site specific constraint in Maptaphut location, the analysis shows that LNG integration with the gas separation plant (GSP) option is selected. The GSP-LNG integration option is chosen because it is the most appropriate technology to be applied as the LNG cold energy utilisation technology in Maptaphut LNG receiving terminal in Thailand due to its characteristic that can fulfil and offer the most appropriate value on the economical, environmental, social criteria and business strategic fit of owner company at the same time. Thermodynamic analysis of the selected technology show that the GSP-LNG integration plant can save up to 42 MW of electrical consumption and generates around 27% less exergy loss when compare to the GSP-LNG receiving terminal standalone system.

Keywords: LNG Cold Energy Utilisation, Technology Selection, LNG Receiving Terminal, Analytical Hierarchy Process, Technology Strategy, Gas Separation plant

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CHAPTER 1
INTRODUCTION

1.1. Rationale / Problem Statement

1.1.1. Rationale

Thailand natural gas demand is surplus supply from domestic resources. Domestic production can produce around 2,800 million cubic feet per day (mmcfd) while the demand is around 4,500 mmcfd [1]. To balance the country demand and supply, PTT Public Company Limited, Thailand National Oil Company (NOC), imports natural gas from Myanmar through a pipeline and constructed LNG receiving terminal to import LNG (Liquefied Natural Gas) to securely diversify energy sources for the country. Focusing on the energy efficiency of LNG receiving terminal operation, at the present, the process to transform liquid natural gas to natural gas in gas phase uses seawater to boil LNG from minus one hundred and sixty three (-163) degree Celsius to be gas phase at fifteen (15) degree Celsius. During this regasification process, massive amount of seawater is required to pump through LNG vaporiser units then leave the units at lower temperature. This seawater temperature is cooled down and discharged back into the ocean without generating any added value on the surrounding environment.

By this situation, study on energy efficiency and energy conservation in LNG terminal where benefit from LNG cold during regasification process is wasted into seawater is rational of the research. LNG cold utilisation technologies as shown in figure 1.1 have to be identified and utilised to capture this wasted energy. When the awareness of LNG cold energy utilisation is raised, from a number of LNG receiving terminals which is gradually increasing all over the world, the effective use of this cryogenic energy will increase energy efficiency of the system which, eventually, increase energy efficiency of global energy usage.

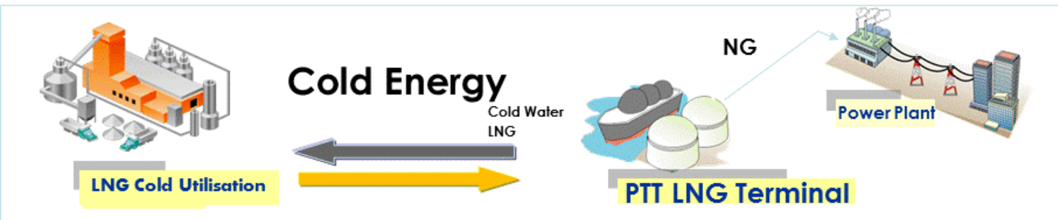

Figure 1.1: LNG Cold Energy Utilisation Potential

In terms of economical logic, as shown in Figure 1.2, when purchasing LNG, around 1,000 USD/ton [2] has to be spent in LNG cost structure for the liquefaction process. This means LNG importer has to pay for the coldness in LNG thus it should not be waste into environmental without making any benefit and value from that payment.

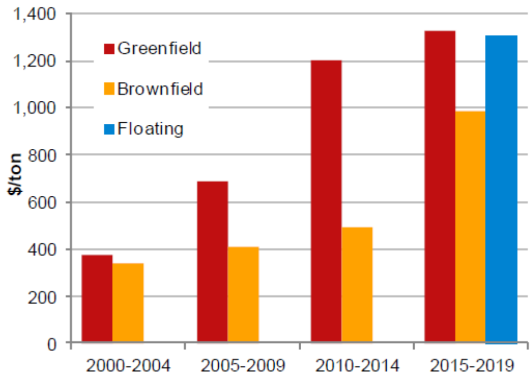

Figure 1.2: Average Liquefaction Unit Cost in USD/ton [2]

The main approach of this research is to tackle technical and non-technical issues by initiating the best technology assessment model to select the appropriate LNG cold utilisation technologies that will harvest benefits from LNG cold at LNG regasification terminal.

1.1.2. Problem Statement

The problem statement of the project is identified as "What are the Best LNG Cold Utilisation Technologies for LNG Regasification Process at LNG Receiving Terminal". And the best solution to this should offer both System Economical Feasibility and High Energy Efficiency to the terminal and society.

1.2. Literature Review

To gather all LNG cold utilisation experiences all over the world, a literature review of the project was done to analyse the existing stage of this technology. Literature results are summarised and illustrated as the set of question and answers in 3 parts.

1. How much energy can we save? : Estimated amount of cold energy that can be harvested at the terminal. This is to see the potential amount of available energy that we can recovery back as a value added to the whole system.

2. What do people do to this all around the world? : Utilisation of LNG Cold which has already been applied in the world. This is to investigate the case study and best practice of the existing terminals how they performed their success profile or managed failure path.
3. How do we know that the selected option is the best option? : Application of Analytical Hierarchy Process (AHP) on technology selection and evaluation. This is to find and select the appropriate tools to screen, prioritise and select the best technology. AHP is one of the best worldwide multi criteria decision making tools that we see its potential to be applied.

From the literature review, it was possible to identify and scope the best research methodology and support the study with sufficient theory, facts and figures to ensure the best project results.

1.2.1. Estimated amount of LNG cold during regasification process

The LNG terminal has the function to vaporise LNG to become natural gas and supply it to pipeline network, this function calls regasification process. Regasification process requires heat input to vaporise LNG from liquid phase to be gas phase which, in general, sea water will be pumped into the system as the heat source to vaporise -163 degree Celsius LNG in vaporising unit.

In order to estimated the amount of LNG cold, Maptaphut LNG Receiving Terminal in Thailand was selected to analyse as a case study to evaluate the amount of LNG cold. Maptaphut LNG Receiving Terminal has 5 MTPA (million tons per annum) capacities but for the first phase operation, terminal will be operated at only 1.5 MTPA regarding to information from Natural Gas PTT Business Plan. As show in figure 1.3, this amount of 1.5 MTPA LNG requires 42 MW of heat to vaporise it to become gas phase (Approximately 838 kJ/kg of LNG is absorbed when LNG temperature is risen from -160 °C to 0 °C). In turn, this is the amount that we will be able to recovery if we can match the heat sink and heat source of the potential system with the terminal operating condition.

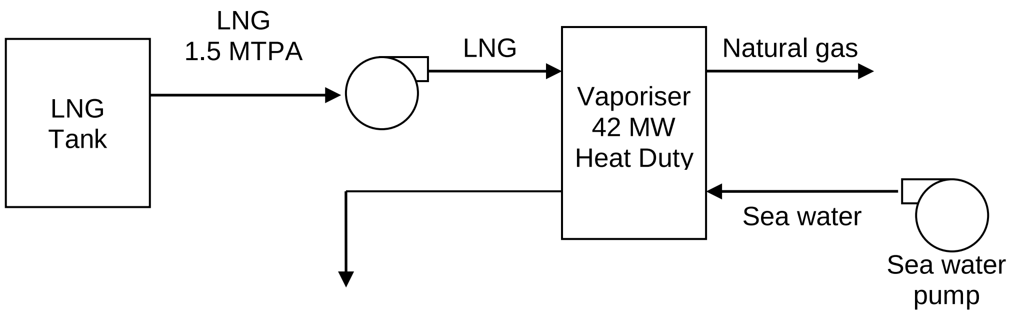

Figure 1.3: Regasification process diagram at LNG receiving terminal

Since we know that LNG is usually transferred through pipelines in the liquid phase and its temperature has to be kept under -163 °C to prevent vaporisation, at this cryogenic temperature, effective high cost pipeline insulation is required. Heat loss and pressure loss rate increases when pipeline length increases thus distance between LNG Terminal and LNG cold utilisation unit has to be minimised. A distance of 2 to 3 km between and the terminal and cold utilisation unit would be the maximum practical limit.

1.2.2. Utilisation of LNG Cold

In regasification process, LNG absorbs heat from a heat source (usually seawater) to raise its temperature up until the boiling point, which in turn cools down the temperature of that heat source. In a general regasification process, seawater is usually used as a heat source of the process and its temperature will be cooled down after the process without making and benefit to the system. This situation is the original idea of where LNG cold utilisation comes from. Energy and cost of energy which is concealed in LNG should not just be wasted into surrounding; harvesting technology should be identified and applied to make the most out of it.

The utilisation of LNG cold means how to effectively utilise the benefits of LNG cryogenic temperature during its vaporisation process. Amount of required latent heat and sensible heat under its very low level temperature (-163 degree Celsius) are the main factors to identify what is the potential heat exchange process can be utilisation of LNG cold.

By matching the amounts of heat and temperature level within the LNG regasification process, eleven (11) LNG cold utilisation techniques to cover all potential industrial sectors can be identified as follows.

1. Integration of LNG regasification process with air separation and liquefaction process (ASU-LNG Integration Plant)
2. Integration of LNG regasification process with gas separation plant process (GSP-LNG Integration Plant)
3. Integration of LNG regasification process with liquefaction and solidification of carbon dioxide production process (LCO2-LNG Integration Plant)
4. Integration of LNG regasification process with cryogenic power generation process (Rankine Cycle)
5. Integration of LNG regasification process with cryogenic power generation process (Direct Expansion)
6. Integration of LNG regasification process as a heat sink for the chemical industry
7. Integration of LNG regasification process with Boil-Off Gas (BOG) liquefaction system
8. Integration of LNG regasification process with freeze seawater desalination process
9. Integration of LNG regasification process with gas turbine process (to increasing turbine efficiency)
10. Integration of LNG regasification process with the refrigeration and freezing process (in warehouses and frozen food or etc.)
11. Integration of LNG regasification process with snow flake production process (for artificial production snow in amusement winter park)

The technical aspects and operating principle of potential LNG cold utilisation technologies above are explained in Table 1.1.

Table 1.1: LNG Cold Energy Utilisation Technologies and Their Features

LNG Cold Energy Utilisation	**Principle of Operation with LNG Cold Energy Utilisation**	**Product/Benefit**
Integrate with air separation and	Integrate LNG stream with air separation and liquefaction process in order to	Liquid nitrogen, oxygen and argon /

liquefaction	produce liquid nitrogen, oxygen and argon. LNG is used as cold source of the system to reduce power consumption in the process.	reduce system power consumption

Table 1.1: LNG Cold Energy Utilisation Technologies and Their Features (Cont')

LNG Cold Energy Utilisation	**Principle of Operation with LNG Cold Energy Utilisation**	**Product/Benefit**
Integrate with gas separation plant	Integrate LNG stream with propane and ethane separation process to reduce power consumption from the system.	Reduce GSP system power consumption
Integrate with liquefaction/ solidification of carbon dioxide production	Integrate LNG stream with liquid carbon dioxide production process. LNG is used as cold source of the system to reduce power consumption in the process.	Liquid CO_2, Dry iced / reduce power consumption
Integrate with cryogenic power generation (Rankine Cycle)	Use LNG as heat sink of the system in Rankine Cycle power generation which has propane as intermediate medium and has seawater as heat source.	Electricity/ electrical energy with free operating cost
Integrate with cryogenic power generation (Direct expansion)	Use high pressure LNG from LNG pump to expand through direct expander turbine to produce mechanical power to drive generator for power generation.	Electricity/ electrical energy with free operating cost
Integrate with chemical industry	Integrate LNG stream with industrial process which require cold source or heat rejection for reducing overall power consumption of the process.	Reduce system power consumption
Integrate with Boil-Off Gas (BOG) liquefaction system	Use PCM to extract heat from BOG to make BOG condense and become LNG again.	LNG re-liquefaction/ Reduce power cost
Integrate with	Use LNG as a cold source of system to	Fresh water/

seawater desalination	freeze seawater before separate salt and water in the desalination process	reduce operating cost
Integrate with gas turbine power plant	Use LNG to cool down compressor inlet air of the system to increase overall system efficiency.	Increase system efficiency

Table 1.1: LNG Cold Energy Utilisation Technologies and Their Features (Cont')

LNG Cold Energy Utilisation	Principle of Operation with LNG Cold Energy Utilisation	Product/Benefit
Integrate with refrigeration process	Integrate LNG stream with refrigeration process and use LNG as cold source of the process to reduce power consumption	Chilled air or water / reduce operating cost
Integrate with snow flake production process	Integrate LNG stream with snow flake production process and use LNG as cold source of the process to reduce power consumption	Snow flake / reduce operating cost

Existing LNG Terminal with LNG Cold Utilisation Units

Existing LNG cold utilisation systems have been applied in some LNG terminals around the world, for example in Japan, South Korea and Taiwan. Alternative of cold utilisations which are applied on each terminal is difference depending on individual characteristic of each terminal. Example of existing LNG cold utilisations are shown in Table 1.2.

Table 1.2: Application of LNG cold in the world [3]

Country	LNG Cold Utilisation
Japan	• LNG cold for air separation and liquefaction unit • LNG cold to produce dry ice • LNG cold for cold storage
Korea	• LNG cold for air separation and liquefaction unit
Taiwan	• LNG cold for air separation and liquefaction unit

	• LNG cold for power generator
Australia	• LNG cold for air separation and liquefaction unit

Japan is one of the leading countries in LNG cold utilisation technology since it is the world's dominant LNG importer and LNG is the main source of energy in the country, as shown in the statistical data in Figure 1.5. One of the best LNG receiving terminals as an example for LNG cold utilisation technology is Senboku LNG receiving terminal, Osaka Gas Co., Ltd, Japan. The terminal has been operated since 70's and import LNG from Qatar, Oman, Malaysia, Brunei, Indonesia or Australia with terminal capacity of 100 MTA where LNG is mainly used as a supply source of city gas network system around the Osaka and Kansai areas. LNG cold utilisations, which had been applied in the terminal are air separation and liquefaction, cryogenic power generation, boil off gas liquefaction, gas turbine inlet air cooling and cryogenic crushing process, as shown in Figure 1.4.

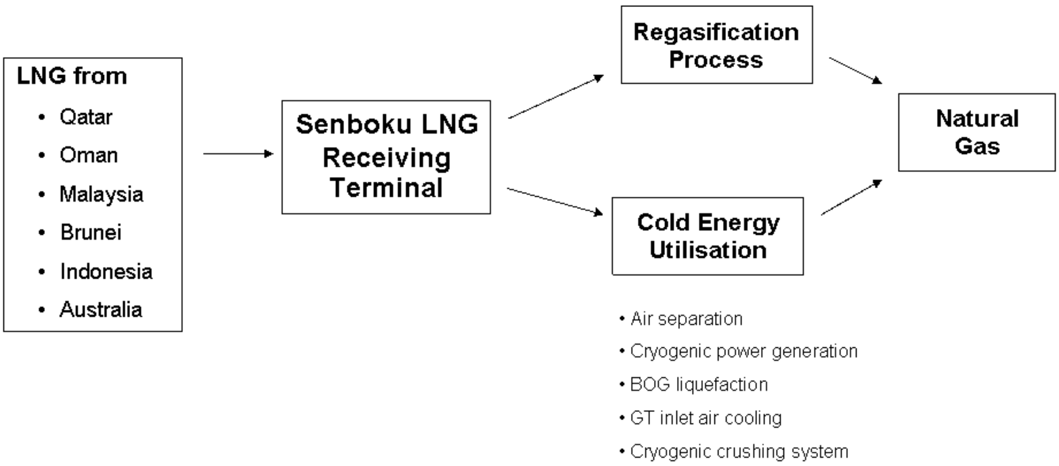

Figure 1.4: LNG cold energy utilisation at Senboku LNG Terminal

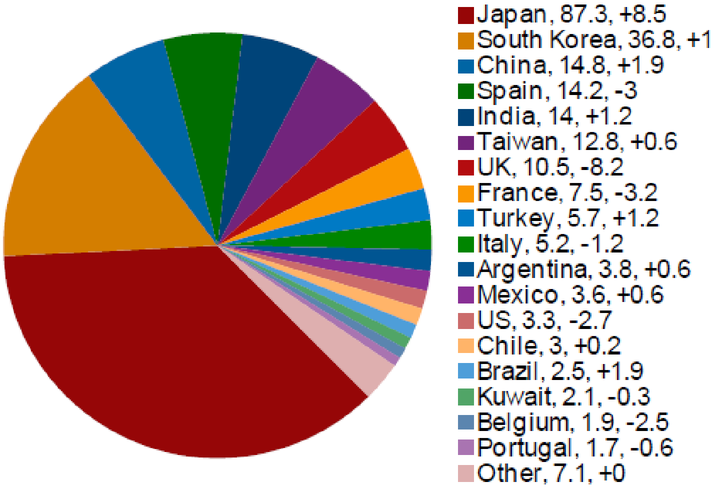

Figure 1.5: LNG Import by country in 2012 [4]

The integration of LNG cold with air liquefaction and separation plant at Senboku Terminal generates amount of liquefied oxygen, nitrogen and argon approximately 7,500 Nm^3/h, 7,500 Nm^3/h and 200 Nm^3/h respectively by the low temperature benefit from 40 t/h of LNG stream. The operator claims that power cost saving by combining cold energy from LNG with the separation and liquefaction process can be reduced to be approximately 50% from total energy cost.

The other applications of LNG cold utilisation at Senboku LNG receiving terminal is the integration with cryogenic power generation. Combination of Rankine cycle which uses propane as a working fluid and LNG direct expansion process can produce 1,450 kW of electrical power output from the system by the 60 t/h of LNG stream.

From the analysis of existing applications and characteristics of LNG regasification process conditions, LNG cold utilisation key success factors can be identified as follows:

1. Cooling temperature: as cooling temperature becomes lower, the advantages of LNG cold utilisation become larger. Due to LNG cryogenic temperatures, LNG cold energy can be utilised more effectively at lower temperatures.

2. Pressure level of LNG: The amount of recoverable LNG cold energy varies largely depending on the LNG pressure determined by the natural gas send-out pressure from the terminal. The LNG pressure influences the design requirements of LNG cold energy utilising facilities, higher pressure of LNG is higher LNG boiling point temperature.

3. LNG load pattern: LNG cold energy utilised facility required LNG steam as a heat sink in the system. Thus, if the LNG cold utilisation facility wants continuously operation, it requires constant quantities of LNG steam to the facility.

4. Site condition: the further a cold utilised facility is away from a LNG terminal, the higher becomes construction cost for LNG line or the low-temperature medium line. Utilising facility should be located as close to the LNG terminal as possible.

5. Reliability: LNG cold utilised facilities are kind of LNG vaporiser for the terminal. It is important that operation of each facility is reliable otherwise the terminal will lose natural gas send-out capacity.

6. Demand and competitiveness of product: for successful cold energy utilisation business, it is essential that products have a demand and competitiveness in the market.

Theses 6 key success factors are the important parameters to be analysed on each option of LNG cold utilisation facility which will be applied in Maptaphut LNG receiving terminal.

1.2.3. Application of Analytical Hierarchy Process

From the analysis of LNG cold utilisation technology in the literature review and the identification of 6 key success factors for success in the LNG cold utilisation business, we can categorise that the selection of best LNG cold energy utilisation at Maptaphut LNG revering terminal is multi criteria decision making problem. Technical and non-technical aspects of LNG cold utilisation alternative have to be evaluated and optimise together at the same time in order to identify the best LNG cold utilised facility option.

Analytical Hierarchy Process (AHP) which is a tool that has been widely used to solve a multi-criteria decision-making problem is selected to be the tools to assist decision making process for the project. To confirm AHP that is a suitability tool for the project, its theoretical and literature review of AHP applications are studied below.

1.2.3.1 Analytical Hierarchy Process Overview

Analytical Hierarchy Process (AHP) is a tool that is mainly used to solve a multiple criteria decision-making problem and it aims at quantifying relative priorities for a given set of alternatives on a ratio scale. Tangible and intangible factors related to the problems are systematically organised based on the principle of Eigen value and pair-wise comparison to create a consistency of the comparison of alternatives and the relationship among the decision factors in the decision-making process.

1.2.3.2 Analysis of AHP Applications

Many outstanding works in many fields have been published in international journals based on an application of AHP. For example: planning, selecting a best alternative, resource allocations and optimisation [5], as shown in Figure 1.6.

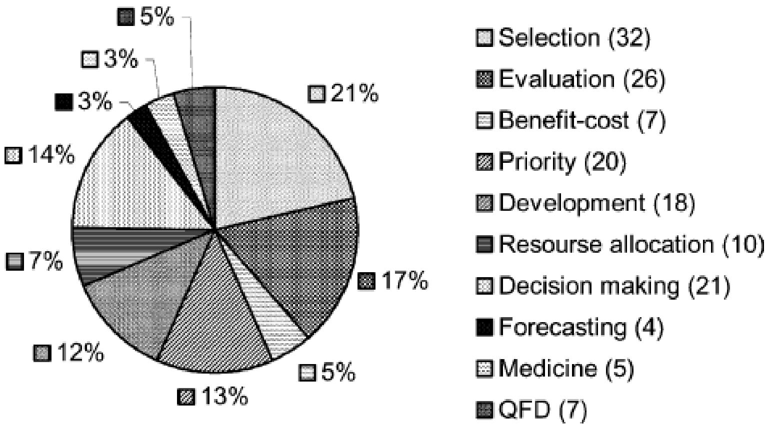

Figure 1.6: Theme specific distribution of review papers

As shown in Figure 1.7, most AHP applications are aimed for selection and decision-making purposes and most of them fall in the fields of engineering, social and personal areas as mentioned in the pie charts.

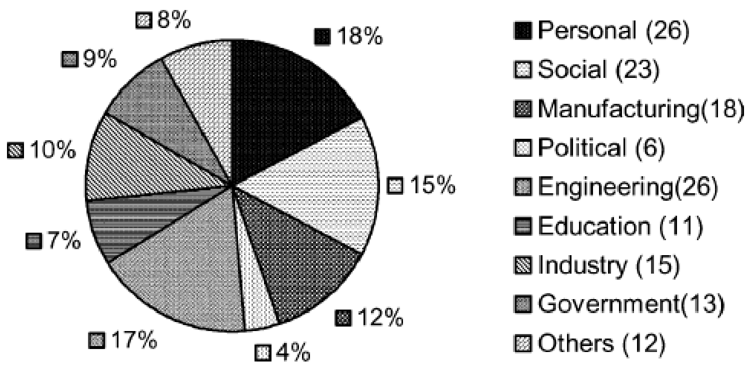

Figure 1.7: Application area specific distribution of review papers

Use of AHP is increasing with time as mentioned in Figure 1.8 and Table 1.3 in countries such as India as well. From the rising and spreading trend of AHP application, this may be indicated that AHP is proved to be more beneficial tool for decision-making process.

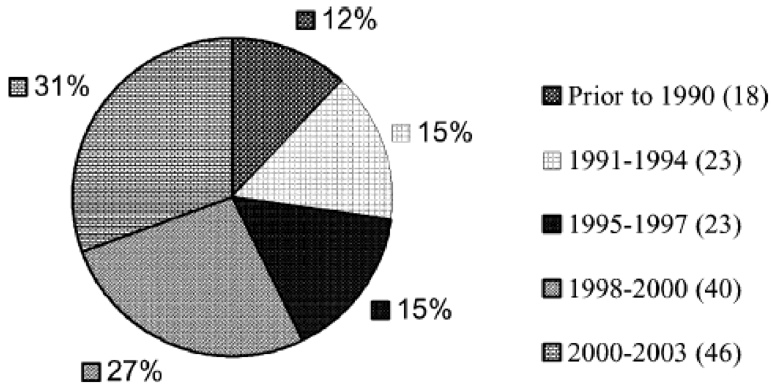

Figure 1.8: Distribution of review papers over the years

Table 1.3: List of country-wise arranged reviewed papers

No.	Country	No. of articles
1	USA	70
2	Finland	9
3	UK	8
4	Hong Kong	7
5	Korea	7
6	Taiwan	6
7	India	6
8	Germany	5
9	Japan	4
10	China	4

Table 1.3: List of country-wise arranged reviewed papers (Cont')

No.	Country	No. of articles
11	Italy	4
12	Saudi Arabia	3
13	Israel	3
14	South Africa	2
15	Turkey	2
16	UAE	2
17	Singapore	2
18	Canada	1
19	Croatia	1
20	Indonesia	1
21	Iran	1

22	Jordan	1
23	Thailand	1

1.2.3.3 AHP Software

Software for AHP by its principle is not too complicated, but it helps to facilitate ease in computation, especially the AHP applications in complex situations that would require professional computer software for calculation times. The sample of well-known AHP software is Expert Choice.

Table 1.4: Literature review Summary

Literature Review Topics	Summary
1. How much energy can we save?	28 MW from 1 MTPA LNG is available to be saved
2. What do people do to this all around the world?	LNG cold energy utilisation concept is to use LNG vaporiser unit as a heat sink for other process
3. How do we know that the selected option is the best option?	How best of LNG cold energy utilised facility depends on both technical and non-technical aspects. This kind of problem can be considered as a multi-criteria decision making problem. Thus AHP which is widely used to assist this type of problem is the appropriate tool to ensure that the result will be the most reasonably best option.

1.3. Research Objectives

Main objectives of the research topic:

- To answer whether LNG cold energy utilisation concept is suitable and feasible for LNG receiving terminal or not.
- To identify what are the key success factors for LNG cold utilisation application which optimise value in both technical and non-technical aspects.
- To develop LNG Cold Utilisation Technology Analysis and Prioritisation framework.
- To test the key success factors effectiveness and LNG Cold Utilisation Technology Analysis and Prioritisation method by utilising them in the case study at Maptaphut LNG receiving terminal.

- To verify the case study results by elaboration of feasibility study on both technological and economical aspects.

CHAPTER 2
THEORIES

2.1. Theoretical Background

In order to select the best LNG cold utilisation technologies for the LNG Terminal, 3 main theories were appropriately selected to be applied on the study. Technology management theory is used to identify and analyse the potential technologies to create technology portfolio, AHP is applied to prioritise the technologies in the portfolio and select the best technologies.

After the best technologies were identified, energy engineering and thermodynamic theory were applied to create a conceptual design of those selected technology into a systems at LNG receiving terminal and then its energy efficiency will be evaluated to ensure the competitive advantage and value creation of the proposed system. Three theories which are mentioned above are briefly described in Table 2.1.

Table 2.1: Theories in the Research

Theory	Overview of Theory	Area Applied and Purpose of the Application
Technology Management and Technology Strategy	*Technology Management* The set of sequential theories in Technology and Competitive Advantage, Technology Analysis, Trends and Forecasting, Acquisition and Technology Transfer which aims to analyse technological fundamentals in scientific ways and then manage them to create competitive advantage.	Technology management concept was applied on the area of LNG cold energy utilisation technology in order to understand the role and value of the technologies, identify possible relevant technologies for the terminal, map technologies to business and market needs and then create a set of high potential technology that can create competitive advantage in the portfolio

Table 2.1: Theories in the Research (Cont')

Theory	Overview of Theory	Area Applied and Purpose of the Application
Technology Management and Technology Strategy	*Technology Strategy* A planned, executable sequence of actions designed to achieve a distinct measurable goal.	Selected LNG cold utilisation technologies were set as the objective of the strategy plan. Internal, external and all relevant parameter both in technical and nontechnical were analysed for the series of tactics which are the key drivers to achieve project goals.
Critical Success Factors Theory	Management theory to find the optimum match between environmental conditions and business characteristics in order to identify and scope all that conditions out as critical success factors.	Technological characteristics which were analysed from technology analysis were used and grouped by the critical success factors concept in order to form the key success factors of LNG cold energy utilisation technology application.
Analytical Hierarchy Process (AHP)	Multi criteria decision making tool which uses the principle of Eigen value and pair-wise comparison to evaluate all factors related to the goal in evaluation process.	After all potential of LNG cold utilisations were identified in the portfolio, AHP was applied to evaluate, prioritise and select the best alternatives of LNG cold utilisation at the LNG terminal.
Energy Engineering and Thermodynamics	First and second laws of thermodynamic to analyse energy efficiency of the system based on mass and heat balance of the system.	First law of thermodynamics was applied to each LNG cold utilisation to evaluate energy efficiency and energy recovery percentage of the system. Second law of thermodynamics was applied on the selected alternative to evaluate and discuss on the issue of useful energy compared to the ultimate limit of ideal process performance.

2.2. Applied Theories for the Research

The theories mentioned in Section 2.1 were reasonably applied on the study step by step to analyse, evaluate and describe the research in scientific and operational terms. The details of each applied theory in the research are explained in the section below.

2.2.1. Technology Management

Technology management in general is the set of management disciplines that allow organisations to understand the role of innovation and technology in order to build an efficient management scheme to maintain a competitive edge in business. Technology management and innovation links engineering, science and management principles to identify, chose and implement the most effective means of attaining compatibility between internal skills and resources of an organisation and its competitive, economic and social environment [6].

In this study, the 3 main concepts of technology management which are selected as research tools are:

1. Technology and Competitive Advantage
2. Technology Analysis, Trends and Forecasting
3. Acquisition and Transfer of Technology

These 3 concepts lead the study to accomplish the objectives of identification of possible technologies and generation of the technology roadmap and portfolio for LNG cold energy utilisation technologies at Maptaphut LNG receiving terminal.

2.2.1.1 Technology and Competitive Advantage Basic Concept

Opportunities for integrating the company's technological resources into and overall technology strategy, interactions between operational functions, development of innovative organisational capabilities to encourage and support the realisation of technology-based opportunities and investment in technology.

2.2.1.2 Technology Analysis, Trends and Forecasting Basic Concept

Technological development analysis and trend forecasting techniques to assist in identifying potential new development and opportunities, evaluation and revolution in product and process technology, invention and innovation, advance manufacturing processes, and product development cycles.

2.2.1.3 Acquisition and Transfer of Technology Basic Concept

Internal and external sources, individual and joint innovation and research, strategic alliances for technological development, managing the transfer of technology within and between organisations, the human skill component of innovative and technological capabilities, learning across development projects.

2.2.2. Critical Success Factors Theory

Critical Success Factors are the limited number of areas in which satisfactory will ensure successful competitive performance for the individual, department or organisation. Critical success factor are the few areas where things must go right for the business to flourish and for the manager to be attained [7].

The concept of critical success factors is clearly inspired by the issue of optimum match between environmental conditions and business characteristics. The surrounding environment is assumed to possess certain fundamental requirements and limitations, threats and opportunities, to which businesses must align their strategy, skills and resources, in order to achieve success.

Five sources of critical success factors as defined by the concept of Rockart are identified below:

- The industry, e.g., demand characteristics, technology employed, product characteristics etc. These can also affect all competitors within an industry, but their influence will vary according to the characteristics and sensitivity of individual industry segments.
- Competitive strategy and industry position of the business in question, which is determined by the history and competitive positioning in the industry.
- Environmental factors are the macroeconomic influences that affect all competitors within an industry, and over which the competitors have little or no influence, e.g. demographics, economic and government legislative policies, etc.
- Temporal factors, which are areas within a business causing a time-limited distress to the implementation of a chosen strategy, e.g., lack of managerial expertise or skilled workers.
- Managerial positions, i.e., the various functional managerial positions in a business have their generic sets of associated critical success factors.

By the application of this theory, all key success factors of LNG cold energy utilisation were identified to ensure that competitive edge on the selected application in business and environment.

2.2.3. Analytical Hierarchy Process

After the technology transfer concept was done and all key success factors were identified, Analytical Hierarchy Process (AHP) theory was applied in order to prioritise and select the best LNG cold energy utilisation technologies for the terminal.

2.2.3.1 Analytical Hierarchy Process Concept in General

Analytical Hierarchy Process (AHP) is a multiple criteria decision-making tool that uses the principle of an Eigen value and the pair-wise comparison to analyse and evaluate each element in the developed hierarchy.

From the fact that the information required for making decision in the selection process comes in both quantitative and qualitative forms, in order to measure qualitative performance as quantitative measurement, methodology to calibrate the numeric scale has to be applied on AHP analytical process. The scales ranges technique is used to standardise all data, the scales from 1/9 for 'least valued than', to 1 for 'equal', and to 9 for 'absolutely more important than' covering the entire spectrum of the comparison. Procedures to construct the hierarchy structure for an evaluation are explained in basic steps below [8]:

1. State the problem
2. Broaden the objectives of the problem or consider all actors, objectives and its outcome
3. Identify the criteria that influence the behaviour
4. Structure the problem in a hierarchy of different levels, constituting goal, criteria, sub-criteria and alternatives
5. Compare each element in the corresponding level and calibrate them on the numerical scale. (This requires n(n-1)/2 comparisons, where n is the number of elements with the considerations that diagonal elements will simply are equal or '1' and the other elements will simply be the reciprocals of the earlier comparisons.)
6. Perform calculations to find the maximum Eigen value, consistency index (CI), consistency ratio (CR), and normalised values for each criteria/alternative.
7. If the maximum Eigen value, CI, and CR are satisfactory then decision is taken based on the normalised values; else the procedure is repeated till these values lie in a desired range.

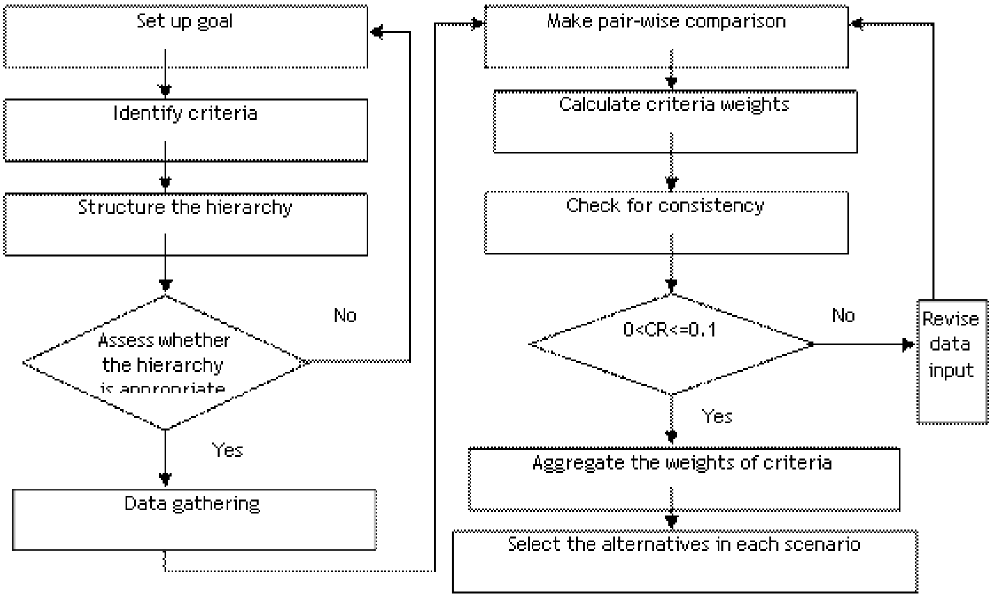

Figure 2.1: Flow Diagram of AHP

2.2.4. Technology Strategy

After high potential LNG cold energy utilisation technologies were selected, technology strategy concept was applied in order to analyse those technologies in detail for the suitable series of tactics that drives the application of those technologies to achieve project goals.

2.2.4.1 Technology Strategy Concept in General

Technology strategy concept itself does not have an instant ready-to-use form of the framework. It is an analytical skill combine with a set of boundary area questions from market & data analysis to internal and external factors analysis of the objective that we study that user have to flexibility, reasonably and creativity apply on to the study in order to generate the best set of tactics to achieve the goals.

Sequential Framework to Generate Technology Strategy consists of main activities as follows:

- **Research:** gathering information of customer, product, market and etc. -> sources of information to be analysed
- **Analysis:** analyse situation, resource, capacity, culture and stakeholder expectations. -> interpret data, explain what data shows in trends and explain that trend

- **Internal Analysis:** analysis of Strength (S) and Weakness (W) -> identify what we have, where we are and etc.
- **External Analysis:** analysis of Opportunity (O), Threat (T), customer and competitors -> identify where opportunity is and avoid where threat is. The useful application is PEST analysis (Political, Economic/Environment, Social/Culture and Technological)
- **Strategic Direction:** identify core competence and capacity, GIDA analysis (Go, Improve, Defence and Avoid.)
- **Strategic Choices:** after we gain all information and conclude it already then we will be able to identify strategic options, evaluate options and select strategy.
- **Strategic Action and Implementation:** plan and allocate resources, organisation structure and design and then put people in charge.
- **Strategic Evaluation and Control:** evaluation plan to measure that can we achieve the goals.

After we have done all theses steps, best LNG cold energy Utilisation Technology will be selected and sequential technology tactics will be generate to ensure the achievement of the technology application.

Table 2.2: SWOT and GIDA Analysis Concept

	SWOT and GIDA Analysis	Internal analysis reviews the business's strengths and weaknesses	
		Strengths	Weaknesses
External environmental analysis takes a look at the opportunities and threat	Opportunities	Go : Pursue opportunities that are a good fit to your strengths	Improve : Overcome weakness to pursue opportunities
	Threats	Defend : Identify ways that you can use your strength to reduce your vulnerability to external threats from competitors	Avoid : Establish a defensive plan to avoid and prevent your weaknesses from making it highly susceptible to external threats

2.2.5. Energy Engineering Theory

After the best choice of LNG cold energy utilisation technology was made for Maptaphut LNG receiving terminal, energy engineering theory especially, thermodynamic laws will be applied to analyse and evaluate energy efficiency of the selected system.

Mainly is to evaluate energy recovery from LNG cold and energy efficiency of the system by first law of thermodynamic. Second law of thermodynamic will also be applied to the LNG cold recovery process to evaluate quantity and quality of the selected system.

2.2.5.1 The First Law of Thermodynamic

The first law of thermodynamics, which is also known as the conservation of energy principle, states that energy can be neither created nor destroyed; it can only change forms. The first law considers that the net work is the same for all adiabatic process of a closed system between two specific states, the value of the net work must depend on the end states of the system only, and thus it must correspond to a change in a property of the system. This simply states that the change in the total energy during an adiabatic process must be equal to the net work done. Two principles which are the main principles for first law analysis are Mass Balance and Energy Balance [9].

Mass balance, which is also called conservation of mass principle, is one of the most fundamental principles in nature. Mass is a conserved property that cannot be created or destroyed but mass (*m*) and energy (*E*) can be converted into each other according to the famous formula proposed by Einstein:

$$E = mc^2$$

where c is the speed of light. This equation suggests that the mass of a system will change when its energy changes. The conservation of mass principle can be expressed as: net mass transfer to or from a system during a process is equal to the net change (increase or decrease) in the total mass of the system during that process. This principle can be written in an equation as:

$$m_{in} - m_{out} = \Delta m_{system} \qquad \text{(kg)}$$

where

m_{in} is total mass entering the system

m_{out} is total mass leaving the system

Δm_{system} is net change in mass within the system

The Energy balance principle states that the net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the energy leaving the system during that process. It can be written in equation form as follow,

$$E_{in} - E_{out} = \Delta E_{system} \qquad \text{(kJ)}$$

where

E_{in} is total energy entering the system

E_{out} is total energy leaving the system

ΔE_{system} is change in the total energy of the system which is the difference of energy between the final state and the initial state

Consider that energy can be transferred in the forms of heat, work and mass, and that the transfer of a quantity is equal to the difference between the amounts transferred in and out, the energy balance can be written more explicitly as:

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})) = \Delta E_{system}$$

where

Q is heat transfer to a system

W is work transfer to a system

E is change total energy of mass

The following is a systematic approach to problem solving by the first law of thermodynamics:

Step 1: Identify the system and draw a sketch of it

Step 2: List the given on formation on the sketch

Step3: Check for special process

Step 4: State any assumptions

Step 5: Apply the conservation equations

Step 6: Draw a process diagram

Step 7: Determine the require properties and unknowns

With sufficient required parameter value, after these 7 steps, all parameters in the system are able to be identified.

2.2.5.2 The Second Law of Thermodynamics

The second law of thermodynamics asserts that energy has quality as well as quantity and actual processes occur in the direction of decreasing quality of energy. As mentioned before that energy has quality and in different forms have a difference grade, thus, in order to have deeper insight into the thermodynamic performance, the work potential of the source that can be extracted as useful work at some specified state is defined as a property which is called Exergy.

The exergy of a flow stream (ψ) is expressed in an equation as

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{v^2}{2} + qz$$

The exergy change from state 1 to state 2 is given by

$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)$$

Exergy can be transferred by heat, work and mass flow, and exergy transfer accompanied by heat, work and mass transfer are given by

Exergy transfer by heat: $$X_{heat} = \left(1 - \frac{T_0}{T}\right)Q$$

Exergy transfer by work:

$$X_{work} = \begin{cases} W - W_{surr} & (\textit{for boundary work}) \\ W & (\textit{for other forms of work}) \end{cases}$$

Exergy transfer by mass: $$X_{mass} = m\psi$$

The exergy balance for any system undergoing any process can be written in equation form as

$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system}$$

or the general exergy balance relation can be expressed more explicitly as

$$\sum\left(1 - \frac{T_0}{T_k}\right)Q_k - \left[W - P_0(V_2 - V_1)\right] + \sum m_i\psi_i - \sum m_e\psi_e - X_{destroyed} = X_2 - X_1$$

where subscripts are i = inlet, e = exit, 1 = initial, 2 = final state and 0 = dead state (surrounding) of the system

After the optimisation theory which is explained in Section 2.2.3 to identify the best portion of LNG cold to be utilised in each selected LNG cold utilisation system, the exergy analysis was applied to evaluate and analyse the selected system based on physical laws which provide ultimate limits on performance of real process.

These 4 main theories were applied in the research and used as scientific tools to select the best LNG cold utilisation technologies, creating the conceptual design of the LNG cold utilisation system at Maptaphut LNG terminal, defining the optimal operating condition for the system and evaluate energy performance of the proposed system as an achievement of the research project.

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

The methodology of the project was created based on science-based approach in order to identify the best method that can create the highest level of Economic Value and Energy Value for the utilisation of LNG at Maptaphut LNG receiving terminal.

The method consists of four main steps as shown in Figure 3.1, which are:

1. Creation of LNG cold energy utilisation technology portfolio and identification of technology key success factors by the application of technology management theory.
2. Development of LNG Cold Utilisation Technology Analysis and Prioritisation Framework. Technology screening and case study selection.
3. Application of the developed framework on case study. Prioritisation and selection of suitable LNG cold energy utilisation at Maptaphut LNG receiving terminal by the application of AHP theory. Finalised selection and feasibility evaluation of selected technology by the application of technology strategy theory.
4. Elaboration and confirmation of energy and economic value of the selected technology by the application of energy engineering theory and exergy concept to confirm the validation of developed method.

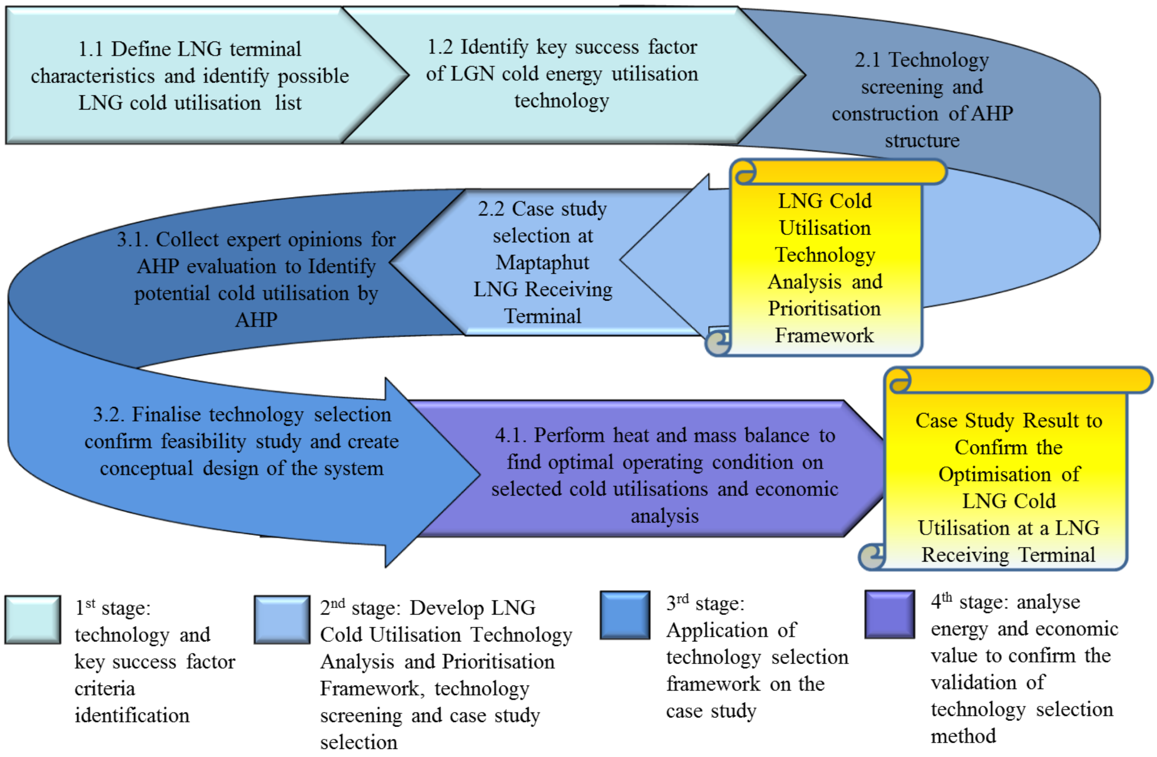

Figure 3.1: Methodology flow of the research

3.2 Research Methodology Framework Setup

Research methodology framework is set as shown in Figure 3.2 from data acquisition to methodology and analysis until result generation as research outcome. The data input into the methodology system can be divided into two categories which are technical data and non-technical data. Technical data consists of type of the system, engineering principle, raw materials, production materials and environmental parameters, etc.

Non-technical data consists of market data, demand and supply of the products, legal, regulations and social impact. Both technical and non technical data were divided into sub-layers and these sub-layer data were collected in order to fulfil all required data, which is sufficient for the model to give the accurate results.

Since this study is not experimental in laboratory, it involves library research and data acquisition rather than substantial experimental fieldworks thus source of data accusation into the study is strictly needed to be selected and confirmed to ensure their precise, accurate, correct, trustable and reliable of data. Only experience resources in natural gas application or at least related engineering and business field are selected to be interviewed and data acquired for the research.

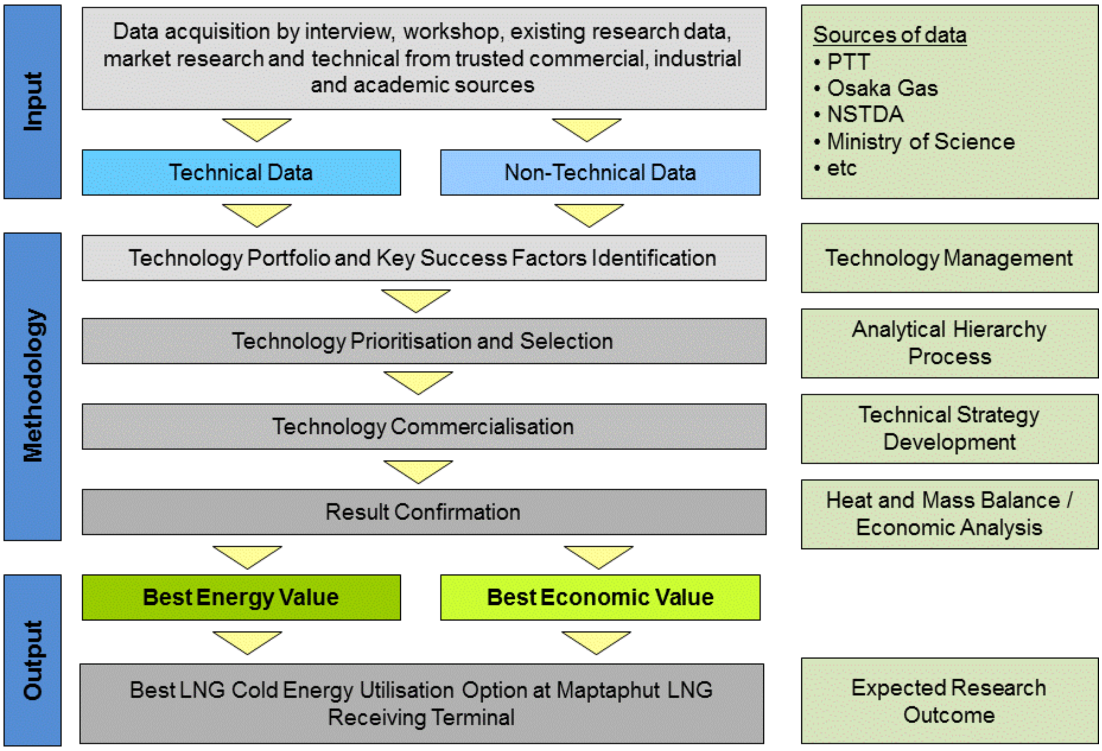

Figure 3.2: Three steps methodology for the research

3.3 Application of Process and Method Used in the Study

3.3.1. Technology Portfolio

3.3.1.1 Identification of LNG Cold Energy Utilisation Technologies

Identification of LNG cold energy utilisation technology to form technology portfolio is done through the data gathering and interviewing process. Since we know that technological innovation can be generated by individual or from linkages between numbers of sources thus to cover most of LNG cold energy utilisation technologies all over the world, data acquisition from main sources of innovation regarding strategic management of technological innovation concept are chosen to be acquired. As shown in Figure 3.2, sources of technological innovation as a system are firms, individuals, private non-profits, government funded research and universities, all of them who have evident works in a natural gas application related fields are chosen to be interviewed to acquire all possible LNG cold energy utilisation technology.

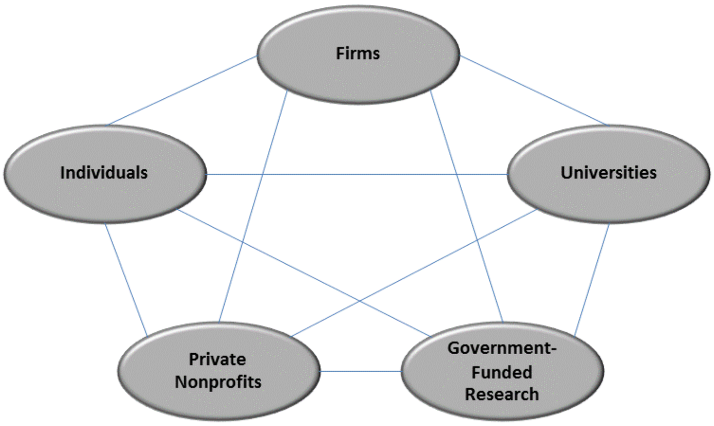

Figure 3.3: Sources of Innovation as a System [10]

3.3.2. Key Success Factors Identification Method

3.3.2.1 Identification of Key Success Factors

By the concept of critical success which is to find the optimum match between environmental conditions and business characteristics under five sources of critical success factors (CSFs) as defined by Rockart, this concept was modified to be compatible with the identification of key success factors (KSFs) in LNG cold energy utilisation technology which is aim to the success in technology transfer rather than management and strategy in firms.

The five sources of critical success factors were rearranged and grouped into 4 key success factors of technology transfer, the industrial factor which is mostly related to the technological and engineering issues is transformed to technical factor. Competitive strategy and industry position factor and managerial position factor which connect to market and strategy issues are converted to economic factor. Temporal factor which relate to the short term situation, apart from the technological and economical which has already allocated in the technical and economic factors, social factor which can be considered as a time period factor is the transformation of temper factor. Since our study is not focusing on the managerial aspect, modification of 5 sources of CSFs to be 4 sources of KSFs which is suitable for technology evaluation in this research is shown in Figure 3.4.

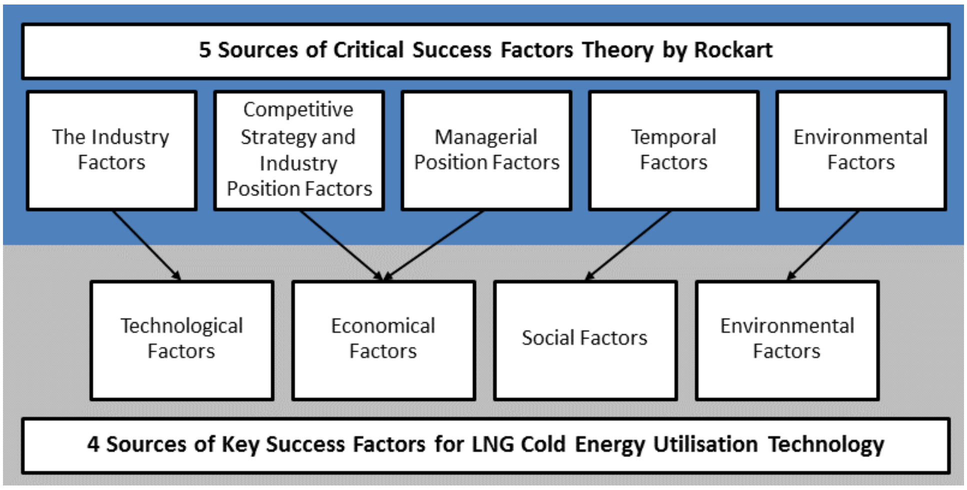

Figure 3.4: Modification of 5 sources of CSFs to be 4 sources of KSFs for Technology Evaluation

After the main sources of key success factors on the LNG cold energy utilisation technology was outlined, interview method for ascertaining critical success factors was performed. Research methodology on this step is to acquire all information from expert who works in LNG business or other related fields also access to all available published information both from business and academic paper to find their views on the key success factor relevant for the technology.

Table 3.1: Four sources of critical success factors and data acquisition method

Sources of Key Success Factors	**Key Success Factors Definitions and Scopes**	**Example Sources of Data Acquisition**
Technological Factors	The factors that have an impact on technology issue. For example energy efficiency of the system, operation condition of the system and required resources.	• For existing information: academic research ,articles, analyst reports interviews and surveys • For new/ emerging trend information: Brainstorm, form key points and structure then populate with information
Economic Factors	The factors that have an impact on the economic issue. For example, supply and demand of raw material and product, competitive advantages of the technology.	

Table 3.1: Four sources of critical success factors and data acquisition method (Cont')

Sources of Key Success Factors	Key Success Factors Definitions and Scopes	Example Sources of Data Acquisition
Environmental Factors	The factors that have impact on environmental issue and constraint. For example, regulatory, political, and demographic changes.	• For existing information: academic research ,articles, analyst reports interviews and surveys • For new/ emerging trend information: Brainstorm, form key points and structure then populate with information
Social Factors	The factors that impact on social issue around the research area. For example, public acceptance, welfare and job creation.	

On the basis of these and flow of KSFs identification as described in Figure 3.5, a preliminary list of factors was compiled which then, in a second round, were analysed and rated on an importance dimension and concluded as key success factors for LNG cold energy utilisation technologies.

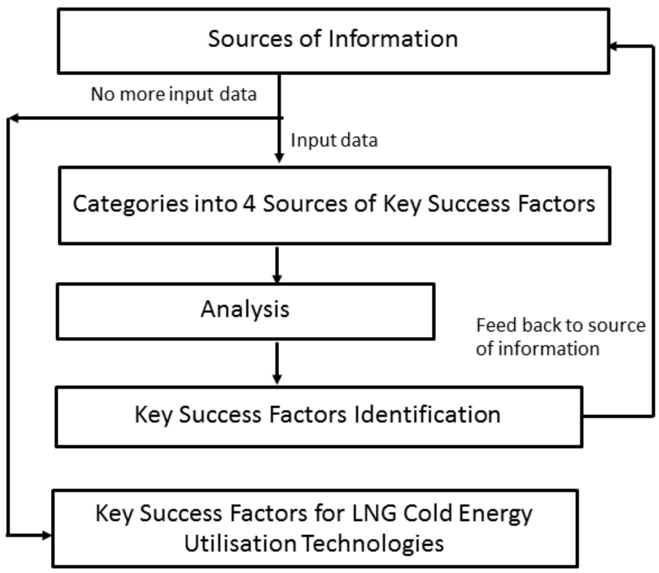

Figure 3.5: Flow of key success factors identification

3.3.3. Technology Screening Method

3.3.3.1 Limitation of Technology Application

In order to screen out the technologies that do not have a possibility to be applied at LNG receiving terminals, the concept of Taxonomy of Limits combines with minimum requirement on each key success factor which has been identified are applied to identify what is the screening criteria of LNG cold energy utilisation technology. Scope of screening criteria is specifically analysed on the application at Mapatphut LNG receiving terminal.

Taxonomy of limits consists of structural limits and performance limits, which are represented by sub parameters as follows:

Structural Limits

- Size and complexity

Performance Limits

- Efficiency, capability, density and accuracy

Combination of the limits above, which is considered as technological limits, with sources of key success factors concept, we were able to identify both technical and non-technical limits, which are technical, environmental, social and safety criteria. Economic criteria is not taken into account since in this study, we have an assumption that the project does not have limitation on economical constraint due to the financial stability of project owner.

3.3.4. Technology Prioritisation by Multi Criteria Decision Making Method

3.3.4.1 AHP for Maptaphut LNG Cold Utilisation

To prioritise technology alternative by AHP method, AHP structure has to be constructed and expert opinions have to be feed in to analyse. Procedures to construct the hierarchy structure for an evaluation are explained in basic steps below [8]:

1. State the problem
2. Broaden the objectives of the problem or consider all actors, objectives and its outcome
3. Identify the criteria that influence the behaviour
4. Structure the problem in a hierarchy of different level constituting goal, criteria, sub-criteria and alternatives
5. Compare each element in the corresponding level and calibrate them on the numerical scale. (This requires n(n-1)/2 comparisons, where n is the number of

elements with the considerations that diagonal elements will simply are equal or ‘1’ and the other elements will simply be the reciprocals of the earlier comparisons.)

6. Perform calculations to find the maximum Eigenvalue, consistency index (CI), consistency ratio (CR), and normalised values for each criteria/alternative
7. If the maximum Eigenvalue, CI, and CR are satisfactory then decision is taken based on the normalised values; else the procedure is repeated till these values lie in a desired range.

Table 3.2: Application of AHP on the study

Hierarchy Structure	Definition of each Hierarchy	Sources of Information on each Hierarchy
Goals	The goal of this study	Research objectives
Criteria	Parameters that represent characteristic of each alternative and have influence on the goal	Key success factors of the technology
Alternatives	All available alternatives that are taken into account on the study	Technology portfolio

After the pieces in each hierarchy is set, a quantitative comparison on the option of each alternative is analysed by formation of a matrix to compare the relationship of each value in hierarchy level two data under the principle of pairwise comparison concept. Input data to the matrix was acquired by the expert opinion interview.

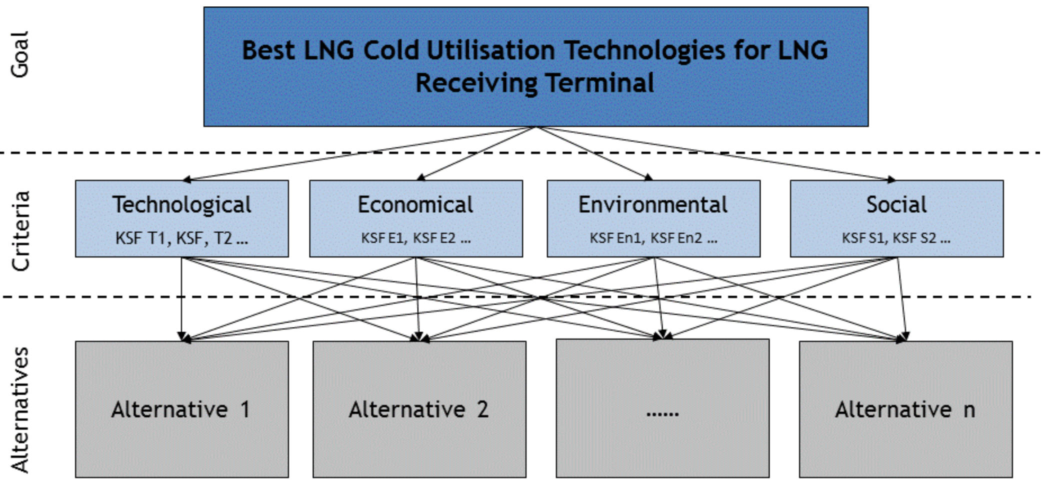

Figure 3.6: AHP Structure

3.3.4.2 Pair-Wise Comparison Criteria

To complete the comparison and prioritisation method by AHP theory, criteria weight matrix was constructed first to evaluate the priority of each criteria against each other. After that each alternative was formed into the matrix to compare against each other under individual criteria. For example, if you have 10 criteria in analysis, 10 matrixes were formed and analysed in order to evaluate alternatives against each other to see the priority of all alternatives against each other under each criteria.

The element a_{ij} in the matric is the quantitative value given for the relative importance the decision maker assigns for the criterion *i* over the criterion *j*. After all the information is filled in and calculated by pair-wise comparison theory, the results of the matrix show the priority of the criteria against each other.

Table 3.3: Matrix to compare the relationship of each value in hierarchy

Criteria	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	…..	Criteria n
Criteria 1	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}
Criteria 2	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}	a_{26}	a_{27}
Criteria 3	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}	a_{36}	a_{37}
Criteria 4	a_{41}	a_{42}	a_{43}	a_{44}	a_{45}	a_{46}	a_{47}
Criteria 5	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}	a_{56}	a_{57}
. . .	a_{61}	a_{62}	a_{63}	a_{64}	a_{65}	a_{66}	a_{67}
Criteria n	a_{71}	a_{72}	a_{73}	a_{74}	a_{75}	a_{76}	a_{77}

For the input value from expert into the matrix, scales ranges technique was used to standardise all data, the scales from 1/9 for 'least valued than', to 1 for 'equal', and to 9 for 'absolutely more important than' covering the entire spectrum of the comparison.

Table 3.4: Scales ranges and definition of relative importance and explanation

Value	**Definition of relative importance**	**Explanation**
1	Equal importance	Two items contribute equally
3	Weak importance of one over another	Judgement slightly favours one over another
5	Essential or strong importance	Judgement strongly favours on over another

Table 3.4: Scales ranges and definition of relative importance and explanation (Cont')

Value	Definition of relative importance	Explanation
7	Very strong or demonstrated importance	The dominance of one over another is demonstrated in practice
9	Absolute importance	One is favoured over another with highest affirmation
2,4,6,8	Intermediate values between adjacent scales	

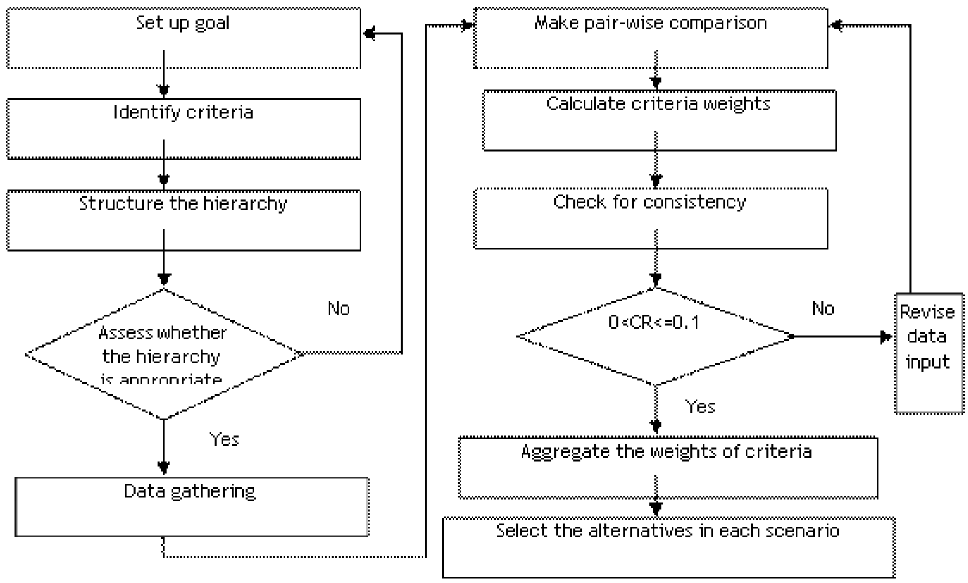

Figure 3.7: Flow Diagram of AHP

3.3.5. Technical Strategy Development

3.3.5.1 Technology Audit

Technological audit concept is applied to determine the gap between the current positions of selected technology, as assessed against set of criteria, and the required (estimated) technological capital needed for the future. Technological capital can only be related to a stated objective for the future and represents the anticipated capability of meeting the stated objective.

3.3.6. Thermodynamic Analysis

First law and second law of thermodynamics were conducted on the selected LNG cold energy utilisation technology in order to identify the detail energy performance of the system and the expected operating conditions at Maptaphut LNG receiving terminal.

3.3.6.1 First Law Analysis

To determine the selected system, following assumptions of steady-state system are assumed:

- The flow in the system is steady
- The state of the working fluid at each specific location within the system does not change with the time
- All components are well insulated
- Pressure drop and heat loss in pipeline are neglected
- Potential and kinetic energy are neglected
- Etc. (depends on each selected system)

Mass balance and energy balance equations were applied to calculate the net efficiency of the selected system, the general form of the equations on each specific location within the system are:

- Mass balance equation:

$$\sum m_{in} = \sum m_{out}$$

- Energy balance equation:

$$Q - W = \sum m_{out} h_{out} - \sum m_{in} h_{in}$$

- System efficiency equation:

$$\eta_{system} = \frac{\sum Energy_{out}}{\sum Energy_{in}}$$

3.3.6.2 Second Law Analysis

Since energy has quality and different forms have difference grades, thus, in order to have deeper insight into the thermodynamic performance, exergy efficiency of the system has to be analysed.

- Exergy function equation (e)

$$e = (h - h_0) - T_0(s - s_0)$$

- Exergy balance equation

$$E_{in} = E_{out} + E_{loss}$$

- Exergy input of the system (exergy change of the heat source)

$$E_{in} = \sum m_{in} e_{in}$$

- Exergy output of the system (net work from the system)

$$E_{out} = \sum E_{output exergy} - \sum E_{consume exergy}$$

$$E_{output exergy} = m_{inlet}(e_{inlet} - e_{exit})$$

$$E_{consume exergy} = m_{inlet}(e_{exit} - e_{inlet})$$

- Exergy efficiency (exergy output divided by exergy input)

$$\eta_{exergy} = \frac{E_{out}}{E_{in}}$$

By the first and second law of thermodynamic analysis, energy conservation, energy efficiency and exergy efficiency of the selected LNG cold utilisation technology at Maptaphut LNG receiving terminal were identified

3.3.7. Economic Analysis

Economic analysis concept is applied to evaluate the economics of a selected technology when applied to Maptaphut LNG receiving terminal. The concept of evaluation will identify the value of selected technology against the option that we did not do anything with the LNG cold.

Under the evaluation, the main concept of the economic analysis is the comparison of money under the same time value which is Net Present Value (NPV).

- Problem solving step for the economic analysis was as follows:
- Set up the cash flow diagram to specify the problem
- Determine what you know and what you are looking for
- Recognise patterns in the cash flows that meet the definition of P, A and F in every respect.
- Identify whether you are doing the problem on a yearly, monthly or some other time basis and make sure the rate and number of periods are consistent with the time period.
- Chose which of the 6 main know equations relating P, A and F you could use to find the amount you are looking for, or use the equation for NPV if appropriate.
- Substitute know values into the equation and solve for the unknown value you are looking for
- Some problems require a two-step conversion, where the unknown cannot be calculated directly.

- Never combine or compare amounts that exist at different points in time. You must convert amounts to the same time periods.

Where:

- P is used to describe a single present amount at point zero in time a the beginning of period 1
- F is used to describe a single amount that occurs at the end of the nth period.
- A is a series of equal amounts that happen at the end of each of n consecutive periods. The periods can be any time period in length, but are usually months or years and the first A occurs at the end of the first period.
- NPV is net present value which present worth of benefits minus present worth of costs
  - When NPV > 0, benefits > costs thus option should be implemented
  - When NPV < 0, benefits < costs thus option should not be implemented

- Assumptions that were used in the study were these following:
  - Depreciation and tax are negligible
  - No incremental in electrical cost

CHAPTER 4
RESULTS AND DISCUSSION

According to the research methodologies developed in Chapter 3, the project results are categorised into 4 parts from technology analysis until technology selection and project feasibility analysis of selected the best LNG cold energy utilisation. Then the result will be discussed and analysed base on the scientific method and theories which have already been mentioned in Chapter 2 to confirm the validity, accuracy and realistic, of the results.

4.1 Results

Project results are categorised into 4 parts which are: (1) Technology and key success factor criteria identification, (2) Technology screening & selection, (3) Feasibility study and system conceptual design generation and (4) Confirmation of energy and economic value. All information is described in detailed section below.

4.1.1 Technology and Key Success Factor Criteria Identification

Systematic approach of technology analysis concepts are applied to gain insight technological parameter and information of LNG cold energy utilisation to ensure the study results that key success factor of LNG cold energy utilisation technology will be accurately identified.

4.1.1.1 LNG Cold Energy Utilisation Technology Portfolio and Its Characteristic

LNG cold energy utilisation concept is the method of using LNG stream as a heat sink or cold source of energy system or process.

In a general regasification process, LNG was vaporised by absorbed heat from seawater at vaporiser unit. LNG is boil from liquid phase at -163 degree Celsius to be gas phase at around 15 degree Celsius and seawater temperature will be decreased around 5 degree Celsius from its inlet temperature. At this vaporiser unit, is where the LNG cold utilisation unit was replaced.

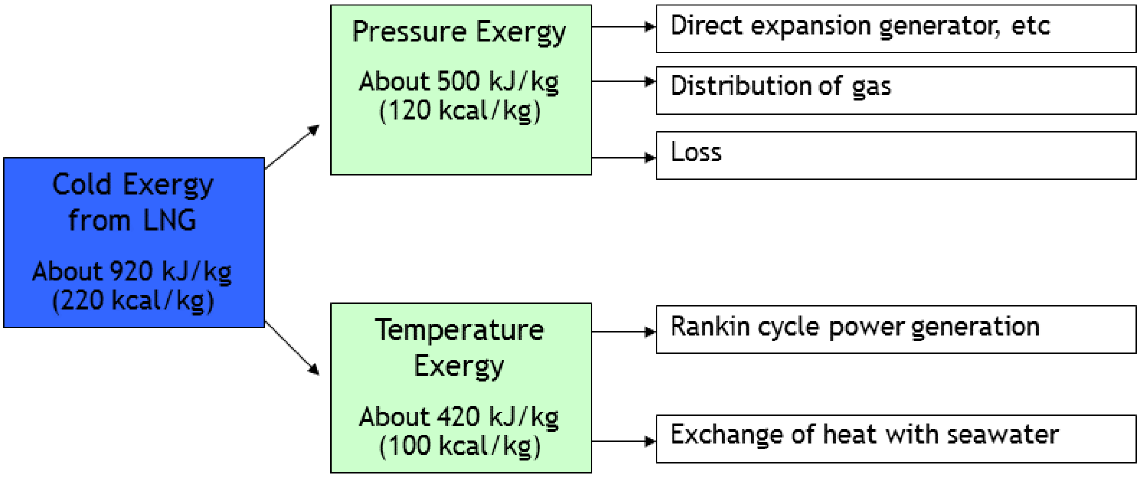

Figure 4.1: Available cold exergy from LNG

The LNG cold energy utilisation technology portfolio is identified as shown in table 4.1.

Table 4.1: LNG Cold Energy Utilisation Technology List

No.	LNG Cold Energy Utilisation Technology	Product/Benefit
1	Integrate with air separation and liquefaction	Liquid nitrogen, oxygen and argon / reduce system power consumption
2	Integrate with gas separation plant	Natural gas and LPG / Reduce GSP system power consumption
3	Integrate with liquefaction/ solidification of carbon dioxide production	Liquid CO_2, Dry iced / reduce power consumption
4	Integrate with cryogenic power generation (Rankine Cycle)	Electricity/ electrical energy with free operating cost
5	Integrate with cryogenic power generation (Direct expansion)	Electricity/ electrical energy with free operating cost
6	Integrate with chemical industry	Reduce power cost of industrial process
7	Integrate with Boil-Off Gas (BOG) liquefaction system	Re-liquefaction LNG / reduce power consumption
8	Integrate with seawater desalination	Fresh water / reduce power consumption

Table 4.1: LNG Cold Energy Utilisation Technology List (Cont')

No.	LNG Cold Energy Utilisation Technology	Product/Benefit
9	Integrate with gas turbine power plant	Increase turbine efficiency / reduce operating cost
10	Integrate with refrigeration process / Chilled water for refrigeration	Chilled water / reduce operating cost
11	Integrated with amusement winter park	Snow flake in winter park / reduce operating cost

Most of the technologies in a portfolio use LNG as a cold source to replace the refrigeration in their original system. From the site visit, interview and available research paper shows that Air Separation Unit (ASU) process required lowest temperature level (-158 degree Celsius; Temperature can be varied depending on designed pressure level of each process owner.) for its system to be operated and chilled water production requires highest temperature level at around 2 degree Celsius to produce chilled water. The other applications required temperature level are between ASU and chilled water production as shown in Figure 4.2.

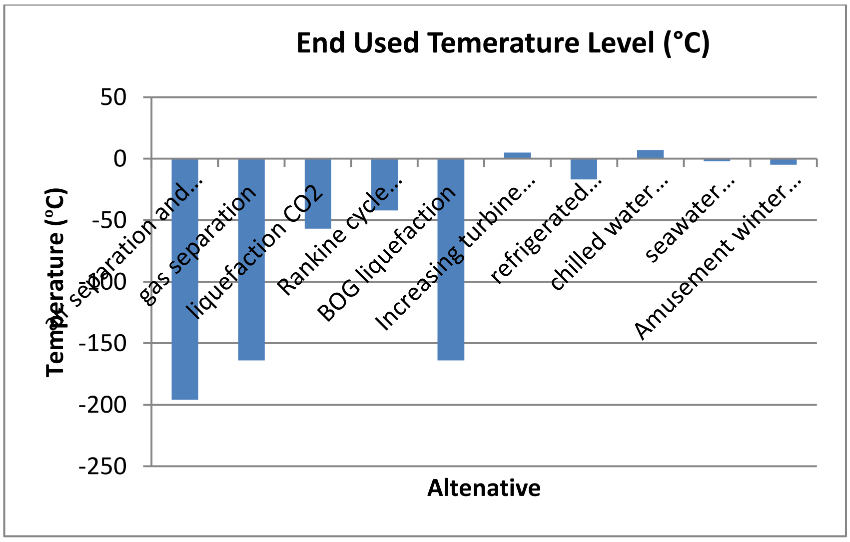

Figure 4.2: Required temperature level of cold source

In terms of system energy consumption, from thermodynamic viewpoints, as cooling temperature becomes lower, the advantage of LNG cold utilisation becomes larger.

Thus, LNG cold energy can be utilised more effectively, substitute more required energy and generate more energy saving at lower temperature as shown in Figure 4.3.

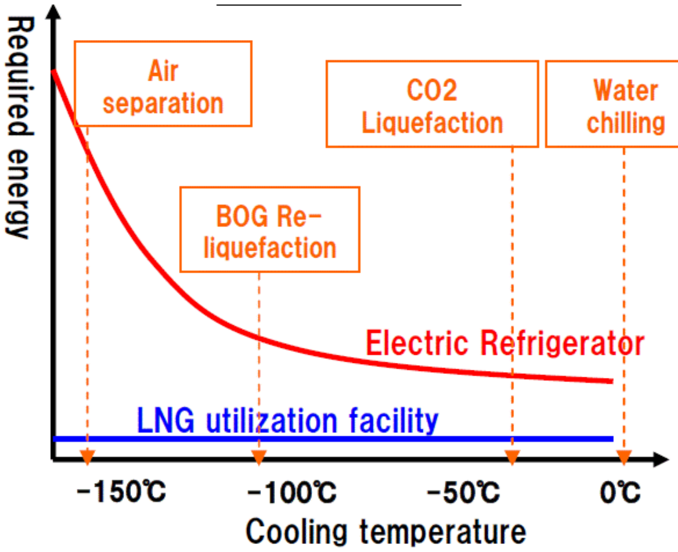

Figure 4.3: Estimated energy required in LNG cold energy utilisation technology [11]

Apart from the cooling temperature required characteristic, pressure level is also one of the parameters that influence system energy consumption. Analysis of the enthalpy of LNG at different pressure level will see that at higher pressure, LNG boiling point temperature become higher.

In general, required pressure level of LNG in the system depends on the designed pressure of send-out gas to natural gas pipeline network. From this thermodynamic property of LNG, the amount of recoverable LNG cold energy varies largely depending on the LNG pressure determined by the NG send-out pressure from the terminal. Thus the LNG pressure influences the design requirements of LNG cold energy utilising facilities and its energy saving potential.

From the main principle of LNG cold energy utilisation that LNG cold energy recovery unit will replace the vaporiser unit in LNG receiving terminal thus, reliability of the LNG cold energy utilisation unit has to be reliable enough to ensure the ability as a vaporiser unit for LNG receiving terminal. It is important that operation of each facility is reliable so as not to hamper stable natural gas network supply.

And from the point that LNG cold utilised facilities are kind of LNG vaporiser, LNG load pattern is important to the system as well. If LNG load pattern to supply to the natural gas network is varied by usage demand depending on time of a day and on a season, this will have a large impact on the system that LNG acts like its cold source. The system will not have a cold source for its operation which would cause the shut down or lower operating capacity of the process.

Generally, LNG cold energy utilised facilities requires constant quantities of cold energy by constant LNG load pattern to ensure their operating/production capacity thus, if the LNG terminal have fluctuated load pattern of LNG, only potion of LNG which are constant as a base load should be taken to utilise in LNG cold utilisation facilities as shown in Figure 4.4.

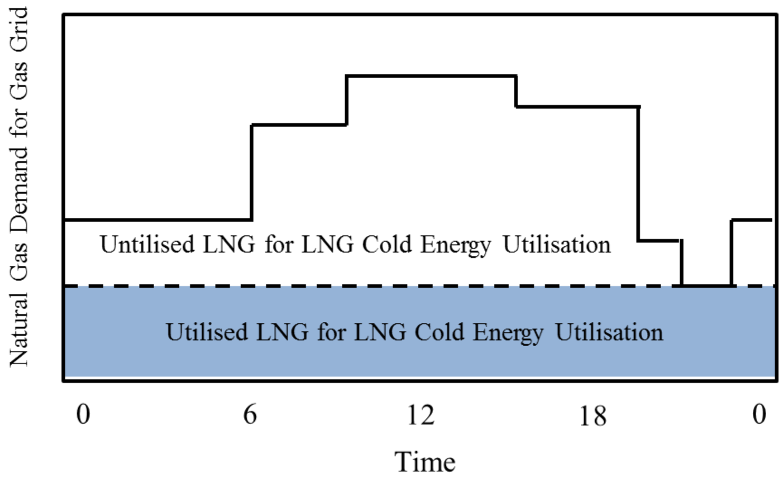

Figure 4.4: Example of LNG load pattern fluctuation at LNG cold energy utilisation concept

Regarding the cryogenic temperature of LNG, the other concern of LNG cold energy utilisation is the site condition of the LNG cold energy utilisation facility. The further a cold utilised facility is away from a LNG terminal, the higher becomes construction and insulation cost for LNG transfer line or the low- temperature medium line. Utilising facility should be located as close to the LNG terminal as possible.

4.1.1.2 Key Success Factor Identification

After all vital characteristics of LNG cold energy utilisation technology are analysed, the concept of 4 sources of key success factors identification mentioned in chapter 3 is applied in order to identify key success factors for LNG cold energy utilisation. Experts interview from the experienced engineer, technician and manager who work in LNG business and operation sectors are the valuable sources of the study which guide to the most accurate and high impact parameters.

After key success factors have been identified and the feedback loop information has been conducted to fine tune the accuracy and validity of parameters. Final result of LNG cold energy technology key success factors are identified as shown in Table 4.2.

Table 4.2: Key Success Factors of LNG Cold Energy Utilisation Selection

Sources of KSFs	KSFs	Definition of KSFs
Technological Factors	% of Energy Recovery (%ER)	How much energy benefit from LNG stream that LNG cold utilisation technique can be extracted as a sensible and latent heat by the principle of difference temperature and pressure
	Reliability of Alternative and LNG Receiving Terminal (RoA)	Since LNG cold utilisation requires LNG stream as a heat sink or coolant of the system, without LNG enters the system, the system will have an effect on its operating conditions and performance. LNG cold utilisation has to work as regasification unit for the terminal thus the system has to have high reliability to satisfy NG demand from customer which is the 1st priority function of terminal.
	Ease of Operation (EoO)	Complexity of the system and level of expertise required to operate the system
	Site Condition (SC)	LNG Cold Utilisation unit has to be nearby LNG terminal to reduce investment in high price LNG pipeline and the utilisation area has to be fit in with the availability land space near LNG terminal (~ 350 rai or 560,000 m^2, maximum distance is 2-3 km)

Table 4.2: Key Success Factors of LNG Cold Energy Utilisation Selection (Cont')

Sources of KSFs	KSFs	Definition of KSFs
Economic Factors	Demand of Product (DoP)	Product that each LNG cold utilisation unit produces has to be on demand in the market or for terminal internal use
	Supply or Resources (SoR)	Availability of resources required to operate the system until obtaining the finished product. It can be explain and measure term of cost of commodity, availability, accessibility and sustainability.
	Competitiveness of Product (CoP)	Saving from the application of LNG cold (baht/kg of LNG) when compare to that system without LNG cold utilisation. Cost of product that each LNG cold utilisation produces has to be lower than the system without LNG in order to make competitive advantages
Environmental Factors	Pollution and Environmental (PnE)	Low (and not excess the limit) CO_2 and VOCs emissions and other pollution which is generated from the system when each LNG cold utilisation is installed
Social Factors	Social Wealth Creation (SWC)	The system generates positive effect on society around LNG receiving terminal and country, for example job opportunity creation.

4.1.2 Technology Screening and Selection

4.1.2.1 Technology Screening

For the technology screening method, screening criteria that fulfils the minimum requirement of LNG cold energy utilisation is identified as shown in Table 4.3. LNG receiving terminal at Maptaphut is selected to be the case study to screen out the unfeasible application.

Screening criteria and the principle of go/no-go gate criteria are applied to screen out some LNG cold energy utilisation alternatives, which their characteristics do not match with minimum requirements of Maptaphut LNG receiving terminal. Main characteristics of Maptaphut LNG receiving terminal, which have strong influence on the application of LNG cold energy utilisation and the new construction of the system, are required to be fully aligned with EIA criteria (should not contain combustion process or VOCs generation), to send out considerably high natural gas pressure in pipeline, to provide constant capacity of natural gas supply rate to pipeline network, etc. All criteria has been constructed and identified as shown in Table 4.3.

Table 4.3: Screening criteria and results

No.	Alternatives	EIA, Social	NG Send-Out Pressure	NG Supply Rate	Commercial LNG Cold Utilisation	Technical limitation	Safety Regulation
1	**Air Separation and Liquefaction**	✓	✓	✓	✓	✓	✓
2	**Rankine Cycle Cryogenic Power Generation**	✓	✓	✓	✓	✓	✓
3	Direct Expansion Cryogenic Power Generation		Low NG send out pressure				
4	Boil-Off Gas Liquefaction System			Required hi-low NG supply rate			
5	Liquefaction and Solidification of Carbon Dioxide	✓	✓	✓	✓	✓	✓
6	Cold Source for Industry					No plant nearby	
7	Seawater Desalination				Only in pilot scale		
8	Increasing Turbine Efficiency					No plant nearby	
9	Gas Separation Plant (GSP)					No plant nearby	
10	Amusement Winter Park						Safety issue
11	Chilled Water Production	✓	✓	✓	✓	✓	✓

The terminal operating condition criteria screened out 3 of LNG cold energy utilisation technologies. Those are direct expansion cryogenic power generation due to low level of natural gas send out pressure, and BOG re-liquefaction by PCM due to the requirement of fluctuation of natural gas send out capacity to enable them to switch their mode to store and emit energy. There is no industrial and gas separation plant and gas turbine plant situated near LNG receiving terminal area so the operations of these 3 alternatives are not practical.

Refrigerated warehouse and amusement winter park are also screened out due to the reason of safety zone around terminal area. The characteristics of refrigerated warehouse and amusement winter park which has a high traffic rate of people in-and-out tend to create difficulty and risk to control all safety regulations in the safety zone. Seawater desalination (freeze desalination) is not applicable since the stage of technology is only in pilot-scale without any availability of commercialization scale in the market at the present.

After the screening method, alternatives of potential LNG cold energy utilisation for Maptaphut LNG receiving terminal are short-listed to only 4 from 14 alternatives, which are:

1. Air separation and liquefaction (ASL)
2. Liquefaction/solidification of carbon dioxide production (LSCO2)
3. Rankine cycle cryogenic power generation (RCPG)
4. Chilled water for refrigeration (CWP)

These 4 alternatives are also the major LNG cold energy utilisation techniques that are widely applied at LNG receiving terminal all over the world.

4.1.2.2 Technology Prioritisation

According to the principle of AHP which mentioned in Chapter 3, the problem is structured into 3 layers with the goal to identify best LNG cold energy utilisation technology at Maptaphut LNG receiving terminal. 9 key success factors of LNG Cold energy utilisation technology are assigned into the structure as AHP criteria in the hierarchy. 4 alternatives which passed screening criteria are the alternatives in the hierarchy.

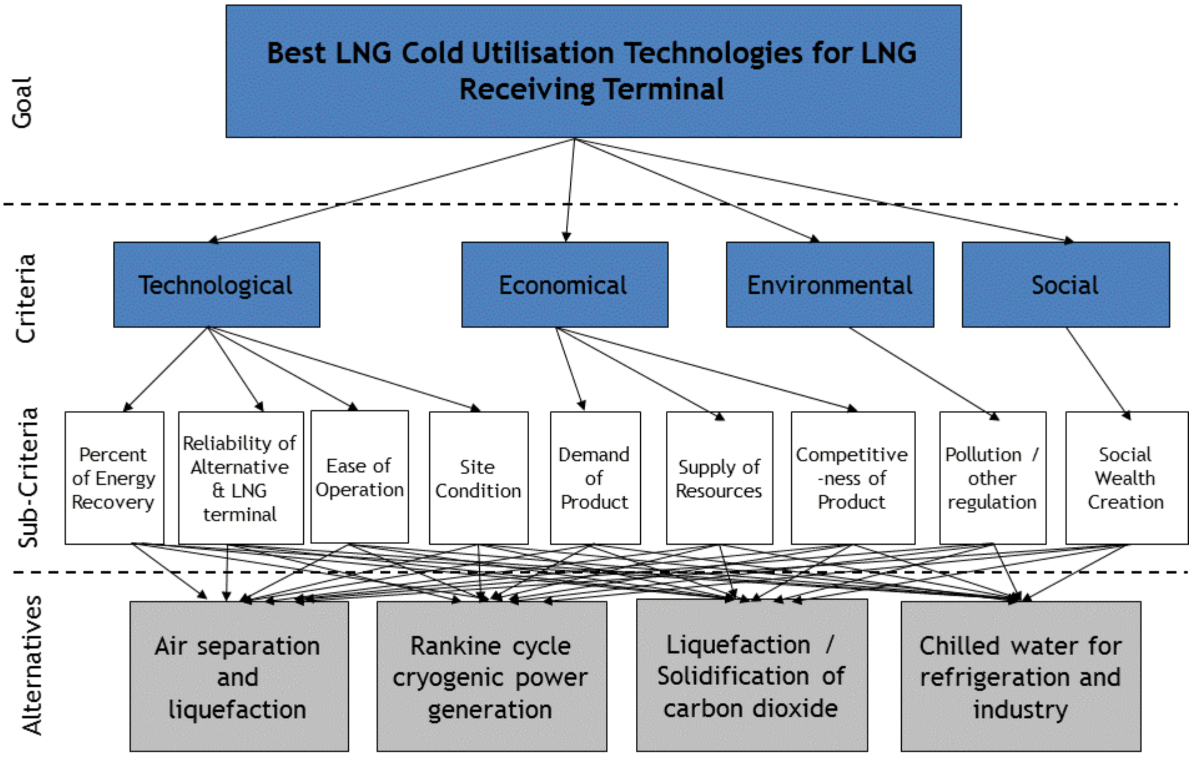

Figure 4.5: AHP structure for LNG cold energy utilisation technology prioritisation and selection

To prioritise the results, two groups of experts from business sector and non-business sector are chosen to give their opinion on the AHP evaluation process. The members of business group are mainly chosen form the energy related sector, and the members from the non-business group are chosen from academic sector, government sector and other non-profit organization who has background know ledge on engineering or energy filed related.

The relative weights of the different criteria, both business and non-business groups, were calculated in Table 4.4-4.5, and the ratings of the various LNG cold energy utilisation technologies under each criteria were evaluated, as shown in Appendies A and B. For the criteria weight, the result from the business group indicated that the most important criteria was the economic aspect parameter, where the highest weight was on competitiveness of product and followed by the supply of resource and the demand of product criteria with the percentages of 24.5, 22.5 and 20.3 respectively. On the other hand, the non-business group, who mostly were the experts from government and academic sector, emphasized on the environmental and social aspects, where the highest weight was given to the social wealth creation (26.5%) and followed by the pollution and regulation criteria (23.1%).

The pair-wise comparisons among the different technologies under each criteria were evaluated as shown in Tables A1-A9 in Appendix A for the business group and Tables B1-B9 in Appendix B for the non-business group. The results from both groups showed the same trend and direction under each criteria, for example, evaluation under energy recovery criteria, air separation and liquefaction received the highest score in both groups of experts.

In the final result of AHP evaluation, the composite weights (overall performance) of the different LNG cold energy utilisation technologies were calculated as shown in Table 4.6 for business group and Table 4.7 for non-business group. The prioritisation result showed that air separation and liquefaction appeared to be the most appropriate LNG cold energy utilisation technology for Maptaphut LNG receiving terminal in the expert opinions of both business and non-business groups with the weight of 39.8 and 45.3 percents respectively. Second priority ranked by both business and non-business groups was also the same, which was Rankine cycle cryogenic power generation with the weights of 27.6 and 18.9 percents respectively.

Chilled water generation was the 3rd priority for the business group and then followed by liquefaction of carbon dioxide as the last priority alternative, while liquefaction of carbon dioxide and chilled water production were ranked 3rd and 4th by the non-business group.

Table 4.4: Pair-wise comparison of the different criteria and their relative weight for business group (Consistency Ratio, CR = 0.0231)

CR=0.0231	%ER	RoA	EoO	SC	DoP	SoR	CoP	PnE	SWC	RW
%ER	1	1/2	1/2	1	1/5	1/5	1/5	1	1	0.0423
RoA	2	1	2	1	1/4	1/4	1/4	2	2	0.0738
EoO	2	1/2	1	1	1/5	1/5	1/5	1	1	0.0499
SC	1	1	1	1	1/5	1/5	1/5	1	1/2	0.0457
DoP	5	4	5	5	1	1/2	1/2	4	4	0.1954
SoR	5	4	5	5	2	1	1	4	4	0.2420
CoP	5	4	5	5	2	1	1	5	4	0.2473
PnE	1	1/2	1	1	1/4	1/4	1/5	1	1/2	0.0443
SWC	1	1/2	1	2	1/4	1/4	1/4	2	1	0.0592
Sum	23.04	16.00	21.50	21.97	6.35	3.85	3.80	21.00	18.00	

Table 4.5: Pair-wise comparison of the different criteria and their relative weight for non-business group (Consistency Ratio, CR = 0.0252)

CR=0.0252	%ER	RoA	EoO	SC	DoP	SoR	CoP	PnE	SWC	RW
%ER	1	2	3	3	2	2	5	1/2	1/2	0.145
RoA	1/2	1	1	2	1	1	3	1/3	1/3	0.078
EoO	1/3	1	1	2	1	1	3	1/4	1/4	0.071
SC	1/3	1/2	1/2	1	1	1	1	1/6	1/6	0.045
DoP	1/2	1	1	1	1	1/2	1	1/5	1/5	0.053
SoR	1/2	1	1	1	2	1	1	1/3	1/3	0.070
CoP	1/5	1/3	1/3	1	1	1	1	1/6	1/5	0.042
PnE	2	3	4	6	5	3	6	1	1/2	0.231
SWC	2	3	4	6	5	3	5	2	1	0.265
Sum	7.37	12.83	15.83	23.00	19.00	13.50	26.00	4.95	3.48	

Table 4.6: Composite weights (CW) of the different LNG cold utilisation technologies given by the business group

	ASL	RCPG	LSCO2	CWP
%ER	0.0253	0.0059	0.0090	0.0021
RoA	0.0065	0.0217	0.0116	0.0339
EoO	0.0036	0.0155	0.0078	0.0230
SC	0.0026	0.0120	0.0056	0.0255
DoP	0.0262	0.1108	0.0105	0.0478
SoR	0.1180	0.0618	0.0112	0.0509
CoP	0.1538	0.0333	0.0487	0.0115
PnE	0.0318	0.0048	0.0048	0.0029
SWC	0.0299	0.0096	0.0161	0.0036
CW	0.3977	0.2756	0.1253	0.2014

Table 4.7: Composite weights (CW) of the different LNG cold utilisation technologies given by the non-business group

	ASL	RCPG	LSCO2	CWP
%ER	0.0856	0.0217	0.0304	0.0069
RoA	0.0065	0.0200	0.0100	0.0415
EoO	0.0043	0.0190	0.0088	0.0387
SC	0.0026	0.0119	0.0055	0.0252
DoP	0.0078	0.0271	0.0028	0.0154
SoR	0.0346	0.0159	0.0034	0.0165
CoP	0.0248	0.0060	0.0090	0.0018
PnE	0.1531	0.0259	0.0398	0.0124
SWC	0.1336	0.0417	0.0760	0.0140
CW	0.4529	0.1891	0.1857	0.1723

4.1.2.3 Technology Selection

From the AHP ranking results, air separation and liquefaction process have the highest potential to be successfully applied with Maptaphut LNG receiving terminal and give competitive advantages on technological, economic, environmental and social aspects.

Although the developed methodology in this study is to cover all technical and economic aspects but in term of creating sustainable value, technological aspect, especially energy efficiency and conservation issue should be highly emphasised when come to the final selection. If we review back to the technology portfolio section, we will see that there is one alternative that has high energy recovery rate as in the same level of air liquefaction and liquefaction application which are the application with Gas Separation Plant.

This application is eliminated in the screening process due to the long term construction plan of Gas Company. However, if time constraint condition is negligible, this should be one of the valuable options of LNG cold energy recovery technology thus for the final technology selection process, technology strategy development concept will be applied and develop by the case comparison between the application of LNG cold energy utilisation with air separation and liquefaction process and gas separation Process.

4.1.2.4 Technology Strategy Development

In order to select the best choices of technology to be applied at Maptaphut terminal, technology, following step of technology strategy development is performed to create a provision of strategy advice in LNG cold energy utilisation technology at Maptaphut LNG receiving terminal.

4.1.2.5 Analysis Step

All information which have been acquired and researched, for example, situation, resources and capacity, culture and stakeholder expectations will be analysed to position the direction and make options through the internal and external factor analysis by the application of SWOT and GIDA analysis.

SWOT and GIDA Analysis

Analysis of internal and external factors against the option that if LNG cold energy utilisation is not applied.

Table 4.8: SWOT and GIDA Analysis on the application with air separation and liquefaction plant

Internal Factors / **External Factors**	Strength • High energy recovery from LNG cold and LNG is own by PTT • High energy saving in the system when compared to the system without LNG application • Lower plant investment cost • Majority of customer is PTT group	Weakness • New/unexperienced business area • No technical know-how in air separation and liquefaction process • The system can't be operated without LNG flow
Opportunity • New line of business • Customer within PTT group • Market demand is still there and situate around terminal area	Go • Construct the plant and sell industry gases to PTT group customers at competitive price	Improve • Improve human resources skill and know how in air liquefaction and separation process

Table 4.8: SWOT and GIDA Analysis on the application with air separation and liquefaction plant (Cont')

Internal Factors / External Factors	Strength	Weakness
	<u>Strength</u> • High energy recovery from LNG cold and LNG is own by PTT • High energy saving in the system when compared to the system without LNG application • Lower plant investment cost • Majority of customer is PTT group	<u>Weakness</u> • New/unexperienced business area • No technical know-how in air separation and liquefaction process • The system can't be operated without LNG flow
<u>Threat</u> • Know how is with others • Existing industrial gas companies which can play price strategy due to their plant breakeven already reached • Rejection on EIA Application	<u>Defend</u> • Negotiate the business model to trade-off between technical know-how and supply of LNG Cold • Merger and acquisition with industrial gas companies or buy in their technology • Sell only LNG cold to ASU • Sell product at competitive price and use internal relationship with in PTT group to make a 3- 5 years contract • Show the energy efficiency merit on the LNG cold energy recovery	<u>Avoid</u> • Avoid build-up air separation plant without supporting from expert and skill-full human resources

Table 4.9: SWOT and GIDA Analysis on the application with gas separation plant

Internal Factors / **External Factors**	Strength	Weakness
	• High energy recovery from LNG cold and LNG is own by PTT • High energy saving in the system when compare to the system without LNG application • Lower plant investment cost • GSP is own by PTT • Strong know-how in GSP process and team	• The system cannot be operated without LNG flow • LPG prices is lower than a global market price due to the market mechanism intervention by government policy
Opportunity • Natural gas demand still increase • Butane and propane (LPG) still has high demand in market	Go • Construct the plant to separate feed gas and supply more natural gas and LPG to market	Improve • Find more sources of natural gas and LNG • Develop innovative process to low down production cost
Threat • Gas reserve in gulf of Thailand is limited • Other players who will invest in GSP business • Rejection on EIA application • Breakthrough in renewable energy to low down its cost to compete with natural gas and LPG	Defend • Allocate feed gas supply in the appropriate proportion to LNG-GSP unit • Offer higher feed gas cost to E&P company due to the energy saving from LNG application • Show the energy efficiency merit on the LNG cold energy recovery	Avoid • Avoid investment only on conventional source of energy by diversify investment to be on renewable R&D and M&A as well

By the comparison with the results of the GIDA analysis between 2 options, we can see that on the Go dimension, strengths from both alternative which is mainly energy cost saving is able to create competitive product and supply to market which still have demand.

For the Improve, Defend and Avoid dimension, we will see that the application with ASU option has high susceptible risk due to lack of in-house knowledge and technological expertise on the air separation and liquefaction process. Outsourcing technological know-how to construct and operate ASU is required.

On the other hand, for GSP application, gas separation process and operation is PTT competency. Also stakeholders which will be taken into account are under PTT business so technology transfer to construct new plant is easier to control and manage.

In term of market, even though both industrial gas production from ASU and natural gas and LPG production from GSP still have demand in the market but it is unarguable that natural gas and LPG has higher demand than industrial gases in quantity due to its larger market size.

By this analysis, to utilise LNG cold with gas separation plant is a good fit option for Maptaphut LNG receiving terminal.

4.1.3 System Conceptual Design Generation & Feasibility Study

Since the GSP option is selected, conceptual design of the system in detail is generated verifying the energy performance of the system and economic feasibility.

4.1.3.1 Conceptual Design of LNG cold Energy Utilisation with Gas Separation Plant Process

General Gas Separation Plant (GSP) process uses compressor and turbo expander process to reduce feed gas temperature in order to extract ethane, propane and butane out from natural gas. At this cryogenic process which use compressor and turbo expander is where to utilise LNG cold energy, as shown in Figure 4.6.

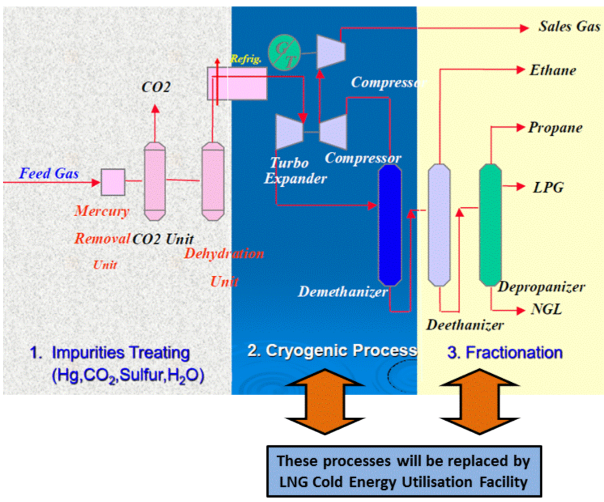

Figure 4.6: LNG Cold Energy Utilisation with GSP

LNG integration to GSP is designed to assist in the propane extraction process. Operating condition will be LNG send out capacity at 1.5 MTPA and the gas plant are sized for 650 MMscfd feed gas. The products from the integrated system will be sales gas (natural gas to pipeline), refrigerated C3 and C4 and NGL as shown in Figure 4.7.

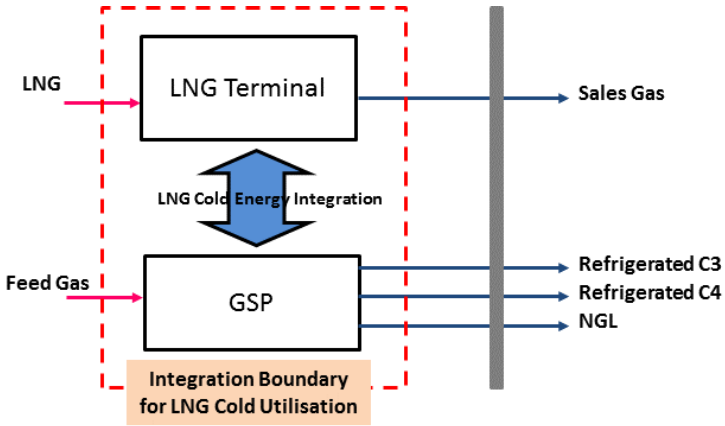

Figure 4.7: Products from an integrated system

The GSP is sized at 650 MMscf/day feed gas intake according to PTT natural gas strategic planning and reserve ratio of natural gas in gulf of Thailand. Feed pressure at the plant inlet is 40 bars and sales gas pressure is 80 bars, 16 degree Celsius due the required injecting condition into gas pipeline network. C3 and C4 will be exported by 20,000 to 80,000 m^3 refrigerated vessels.

LNG terminal will be required to operate in a based load gas send out mode for reliability of the integrated system and the send out ability is maintained to be the same capacity, 1.5 MTPA, as in the system without LNG integration.

In order to compare the benefit of LNG cold energy utilisation, the simplified process flow schemes for the integrated GSP-LNG receiving terminal and Standalone GSP are studied. Block scheme for the study are developed as shown in Figure 4.8.

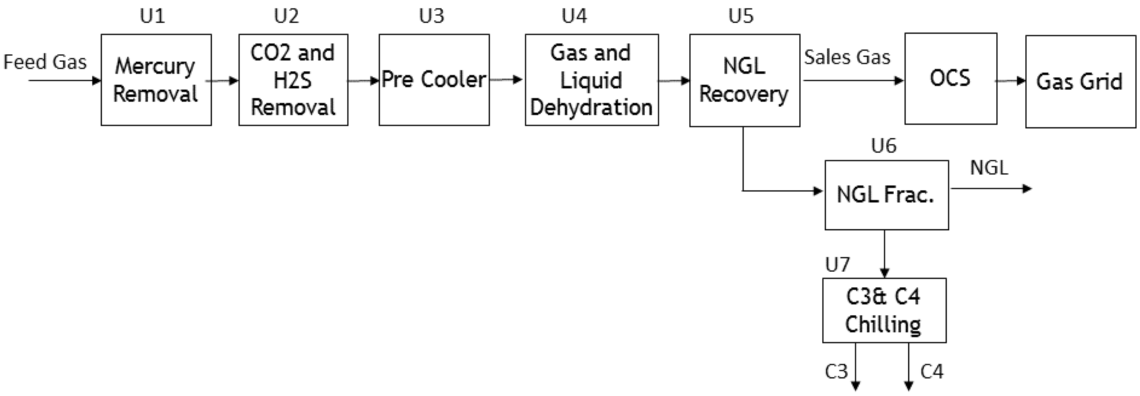

Figure 4.8: Block scheme of GSP

4.1.3.2 The main units are identified as follows:

- Mercury removal unit, U1
- Acid Gas Removal Unit, U2
- Gas and Liquid Dehydration Unit, U3 & U4
- C3+ Extraction, U5
- Fractionation, U6
- Product Chilling, U7

The system is designed to be operated with 1.5 MTPA of LNG according to the LNG import capacity by PTT at the stat up phase and this amount of LNG used in the LPG extraction process at GSP. Analyse on each main unit which mentioned above is described as follows.

Mercury removal unit, U1

Feed gas enters mercury removal adsorbers and flows downwards through the beds. Mercury is adsorbed in the bed by reaction with a metal sulphide to give mercury sulphide (HgS). A cartridge type of filter is installed downstream of the mercury removal beds to remove dust released in the mercury removal beds from treated gas. The gas exits the Mercury Removal Unit and is routed to the Acid Gas Removal Unit.

Acid Gas Removal Unit (AGRU), U2

At this unit, CO2 and sulphurs species are removed from the feed gas. By the Sulferinol process which use solvent in the designed temperature and pressure, feed gas will be heated up and then condensed then CO2 and other contaminates such as H2S, mercaptans and COS will be removed from the feed gas to meet send out gas specification.

Gas and Liquid Dryer, U3 and U4

To avoid freezing in downstream equipment, dehydration process will be applied to residual water content to be less than 1 ppmv. The gas is cooled in the pre-cooling section and then will transfer through Mol Sieve Driers o remove the water out from the gas.

Propane Recovery Unit, U5 and U6

The gas is cooled and pass into a NG feed gas separator and subsequently separated into two phases. Any liquid that condensed out is separated from the cold gas in the inlet separator. The C3+ liquid extract in the de-ethaniser is separated in the fraction train generating liquid products propane, butane and NGL. Propane and butane are refrigerated and stored at atmospheric pressure. NGL is sent to an intermediate storage for individual designed purpose.

4.1.3.3 Cold Integration

Cold LNG at 85 bars, -155 degrees Celsius is supplied to GSP due to the requirement of send out gas and it will be used as the cooling medium throughout the GSP. The geat transfer configuration/network for GSP has been designed such that the LNG will be leaving the GSP at a temperature more than 16 degree Celsius.

There are 2 heat sinks available for the integration process, these are LNG is dense phase (-114 to -155 degree Celsius) and ambient air at 35 degree Celsius. LNG is to be vaporised by the GSP to an exit temperature at 16 degree Celsius and the GSP requires cold duty for its operation as shown in the table 4.10.

Table 4.10: Cold Utility Required in GSP process to extract LPG from feed gas

Cold Utility Requirements			
Heat Exchanger	Description	Hot Side Temperature (°C)	Cooling Medium
HX-1-in	De-C2 condenser	-48	LNG
HX-1-out		-66	
HX-2-in	C3 refrigeration	11	LNG
HX-2-out		-43	
HX-3-in	C4 refrigeration	26	LNG
HX-3-out		-8	

Table 4.10: Cold Utility Required in GSP process to extract LPG from feed gas (Cont')

Cold Utility Requirements			
Heat Exchanger	Description	Hot Side Temperature (°C)	Cooling Medium
HX-4-in	De-C3 condenser	12	LNG
HX-4-out		1	
HX-5-in	De-C4 condenser	28	LNG
HX-5-out		26	
HX-8-in	Propane Cooler	18	LNG
HX-8-out		16	
HX-11-in	De-C4 Bottom product chiller	50	LNG
HX-11-out		27	

Based on the temperature drop required by the GSP process streams, the LNG is heated in the heat exchangers against these streams within the cold integration premises. To fulfil the LPG extraction process, external cold utility for the extraction and fraction operation are listed in Table 4.11.

Table 4.11: Cold requirement for the process

Relevant Column Data				
Column Name		De-C2	De-C3	De-C4
Condenser cold utility		cold utility	cold utility	cold utility
Condenser Duty	MW	-23	-25	-7
Reboiler Duty	MW	21	24	7
Column condenser Temp	C	-66	11	26
Column Condenser Pres	bar	30	6.7	3.2
Column Reflux Ration		0	3	1
Column Reflux Rate	kg-mol/hr	7148	4076	674
Estimated column diameter	m	5.1	3.9	2.2

By all information above, the cold and hot stream have been mapped together as heat exchanger network as shown in Figure 4.9. The temperature profile and estimated duties for the LNG and process streams are shown. The layout map in figure 4.10 shows the heat integration of the LNG stream with GSP plant.

LNG feed temperature at -155 degree Celsius and the last heat exchanger HX-5 pinches with 7 degree Celsius approach. The total cold duty required is 65 MW which requires 2.7 MTPA of LNG.

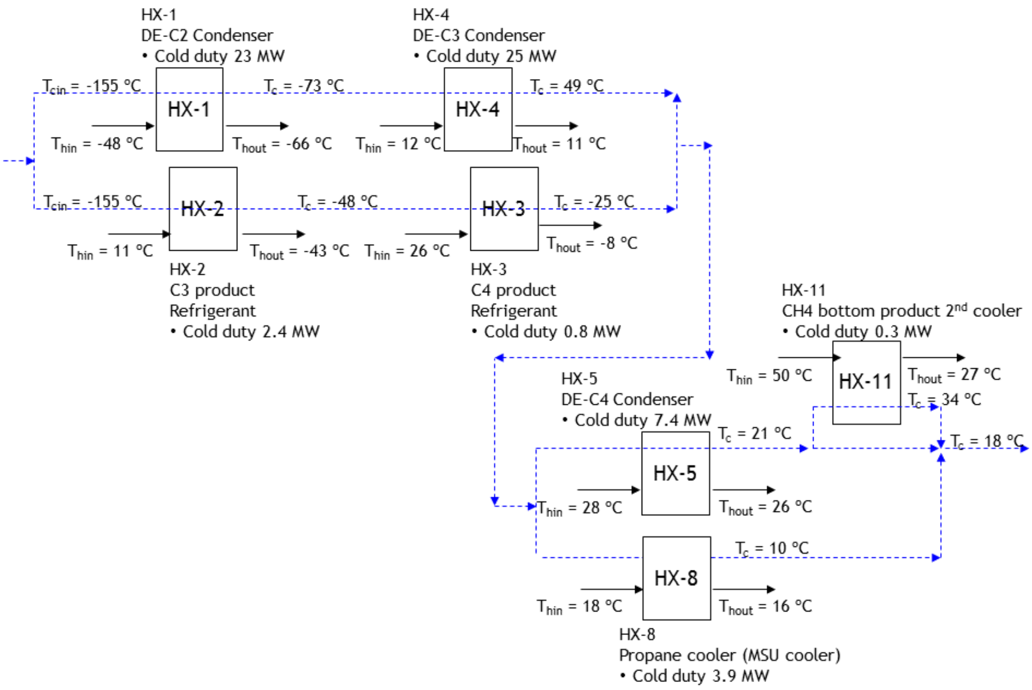

Figure 4.9: Matching hot and cold streams for LNG-GSP integration process

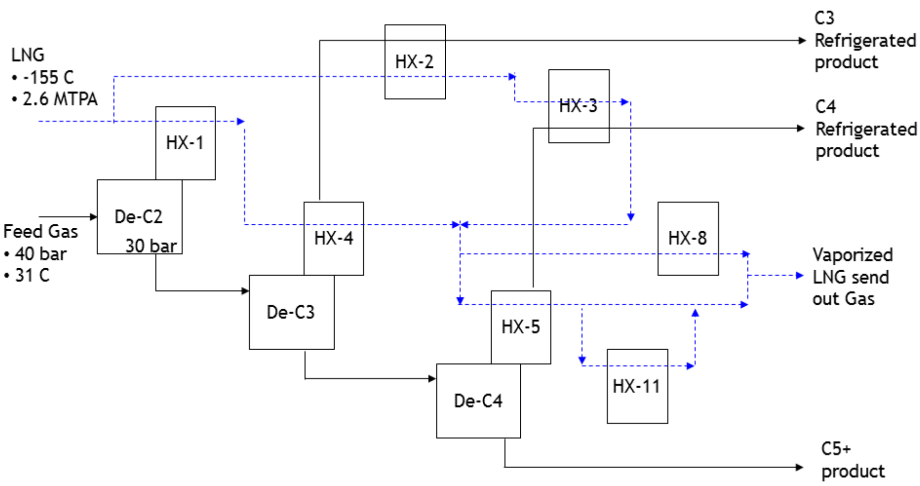

Figure 4.10: Cold integration layout map

4.1.3.4 LNG Supply and Demand

Given the LNG required by cold utilisation and import planning from PTT at the 1st phase of terminal operation, there is not enough cold LNG available to meet the cold demand in the GSP-LNG plant to extract LPG from feed gas. LNG import planning from PTT has to be taken into account for consideration and match the cold demand with cold required from the integrated plant.

Table 4.12: LNG and GSP Roadmap in Thailand

Year	Phase	Terminal Capacity (MTPA)	GSP in Operation	GSP Capacity (MMscfd)	Required LNG for GSP7 (MTPA)	Required LNG for GSP8 (MTPA)	ORV	ORV in Operation
1	1	1.5	7	650	2.8		1+1	
2	1	3	7	650	2.8		3+1	1
3	1	3	7	650	2.8		3+1	1
4	1	5	7	650	2.8		4+1	3
5	2	6	7 & 8	1300	2.8	2.8	4+1	1
6	2	6	7 & 8	1300	2.8	2.8	4+1	1
7	2	6	7 & 8	1300	2.8	2.8	4+1	1
8	2	6	7 & 8	1300	2.8	2.8	4+1	1
9	2	6	7 & 8	1300	2.8	2.8	4+1	1
10	2	10	7 & 8	1300	2.8	2.8	4+1	5

To distribute investment and balance production capacity, GSP 6 is planned to be constructed first and GSP7 will be constructed later and ready to be operated after GSP6 has operated for 5 year. LNG is planned to be imported at the first amount of 1.5 MTPA and follow by 3 MTPA and run in the full capacity of terminal 5 MTPA in the 4th year operation. After that the LNG receiving terminal is planned to expand terminal capacity to reach 10 MTPA in year 10th of operation.

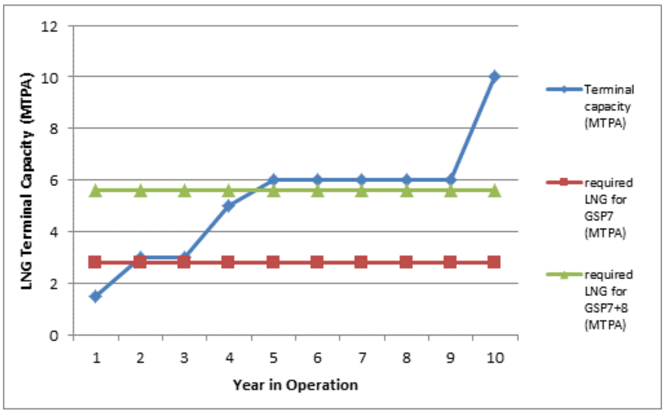

Figure 4.11: LNG Cold Demand and Supply Matching

By the supply and demand of LNG cold available in Table 4.11, we will see that in the first year operation, LNG-GSP plant has to be operated in turndown mode to match the LNG cold available. Full load operation which required 2.8 MTPA of LNG will be achieved in the 2nd year operation for 100% capacity in LPG extraction. When LNG supply is exceeded LNG cold required by LNG-GSP Plant, vaporisers in LNG receiving terminal which is available since 1st phase construction will be used to balance and maintain send-out gas capacity to pipeline network.

4.1.3.5 Design Condition of LNG-GSP Integrated Plant.

After all design constraint is identified analysed, overall mass balance are provided in Table 4.13 for 650 MMscfd GSP for LPG extraction process. 2,409 tons per day of LPG will be produced after 100% capacity of the system.

Table 4.13: Mass balance for the system

Feed Stream	Flow, Tpd
Feed gas	19,708
Product Stream	
Acid gas to FG	344
Acid gas to incinerator	6,396
Sales gas	10,067
Propane	1,530
Butane	879
Condensate	492
Total Products	19,708

4.1.3.6 Saving from the LNG-GSP Integrated System when Compare to Standalone GSP System.

Saving form the integrated system are described into 2 categories which are energy savings and investment savings.

Energy Saving

The impact of the heat integration on the GSP is summarised in the following tables. For the treating unit there is no impact of the heat integration. The total duty of the heat exchanger network in the GSP extraction and Fraction units is comparable between with and without LNG integration on the GSP.

Table 4.14: Impact of the heat integration on extraction process.

		Integrated	**Standalone**
Duty (MW)	Heat exchangers	23.4	29.4
	Air cooler	6	31.6
	LNG	63.2	0
	C3 refrigerant	0	28
	Reboiler	51.8	51.1
	Total	144.4	140.1

The total required compression power is however significantly different between the standalone and integrated system. The differences in compression power between standalone and integrated system are indicated in Table 4.15. The total compression power benefit for the integrated system on the extraction process is 42.4 MW.

Table 4.15: Impact of Integration on GSP Compressors

	Compression power, MW	
Description	Integrated	Standalone
C1 Booster compressor	3.1	26.5
C3 Compressor	0	19
Total compressor power	3.1	45.5

Energy savings in Table 4.15 are only from the main equipment, which are the compressors, if the remaining power consumers equipment, for example, air cooler fans and pumps are taking into consideration, the required power benefit would increase to 43.6 MW.

4.1.3.7 Economic Feasibility Study

After the final choice is selected and provision of strategy advice in LNG cold energy utilisation technology at Maptaphut LNG receiving terminal has already been identified in the above section, a feasibility study especially in the economic analysis is performed to ensure the value creation on this strategic direction. Economic feasibility study is analysed based on the comparison between standalone GSP and GSP-LNG terminal, capex and opex of both case will be identified regarding to the design concept that have been indicated.

For the treating units, there will be no cost difference between the standalone and integrated GSP-LNG terminals. Capex saving are identified between an integrated and standalone GSP due to the following major hardware differences;

- Absence of expander-recompressor system in the integrated system
- The use of expensive air coolers in the fractionation section of the GSP instead of the specified compact PCHE type exchangers using LNG refrigerant
- No need for an external C3 refrigerant system in the case of an integrated GSP system
- 30 MW less power generation requirement for the integrated GSP system

Table 4.16: Cost saving integrated GSP-LNG terminal versus standalone GSP

Capex benefit in the GSP plants	
	Capex Benefit (MM$)
Propane Extraction GSP 7*	175
Propane Extraction GSP 8*	175
Total saving	350

*Price including 22% contingency and 15% EPC premium

The LNG terminal itself also gains capex benefit due to the reduction of ORV capacity. The cost saving is resulting from the saving in civil cost for the reduced seawater intake/outfall system, the reduction in ORV capacity, the reduction in seawater pumps and some reduction in required power generation capacity. During phase 2 terminal expansion from 5 MTPA to 10 MTPA, additional 5 MTPA ORV capacity is eliminated by the substitution of integrated GSP-LNG system which generate saving around 58 million USD.

Table 4.17: Cost benefits for the LNG receiving terminal integration in 2 cases.

Capex benefit in the LNG terminal	
	Capex Benefit (MM$)
EPC (4+1 ORV in phase 1 and no ORV in phase 2)	58

The opex saving for GSP-LNG system is estimated at 20.7 million USD per annum by assuming a fuel price of 4 USD/MMBtu based on the delta net fuel gas requirement between the standalone and integrated GSP. The opex saving for the LNG receiving terminal is estimated to be 1.5 million USD per annum (340 days/annum) due to less seawater pumps power consumption. In terms of CO2 emission, the befit of integrated GSP-LNG system is estimated to be 1054 tpd for GSP7 and 8 cases.

Table 4.18: Opex benefit for GSP integration system

Opex benefit of the integrated plant	
	Opex benefit (MM$/year)
GSP 7&8	20.7
LNG Terminal 4 ORV	1.5

On the assumptions that the GSP-LNG terminal life cycle is 20 years, and the hurdle rate is 10%, and due to long term projects, salvage cost is negligible. Since exact information on the total investment of GSP is difficult to acquire and products from GSP which are Natural Gas and LPG have price variation based on market segment and selling volume, thus, NPV and IRR of total plant investment on GSP-LNG Integration will not be calculated to avoid inaccuracy result.

Only saving portion from plant investment (capex) and operating cost (opex) that can be acquired from the study and interview are taken into calculation. Time value concepts are applied and present value of saving from both capex and opex of the project is calculated to be 490.3 million USD.

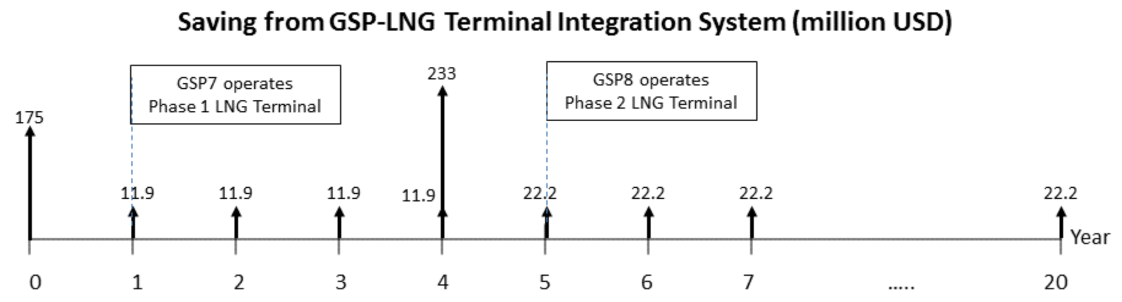

Figure 4.12: cash flow of saving on the LNG-GSP project in 20 years

4.1.3.8 Thermodynamic Analysis

After the system concept has been designed, the energy recovery potential of the selected system is evaluated based on the first and second law of thermodynamic analysis to analyse both quantity and quality of the selected system.

The amount of energy we can extract as useful work is of interest, but the rest of the energy is not worthy of our consideration. To determine the useful work potential of a given amount of energy at some specified state. The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system.

To confirm that GSP-LNG integration can generate benefit from cold energy recovery, scenarios of the GSP-LNG integration versus GSP and LNG Terminal Standalone are calculated to compare energy saving and exergy loss between each other.

4.1.3.9 Calculation of exergy values

The physical component of the exergy value of a mass flow is calculated from the enthalpy and entropy values, as in the equation below.

$$Ex_{m,ph} = \dot{m}[(H - H_0) - T_0(S - S_0)]$$

4.1.3.10 Exergy potential of LNG

LNG is stored at 1 bar, minus 163 degree Celsius in the tanks and when it will be utilised, it will be compressed and vaporised to meet the conditions of the gas network, which are about 80 bars and 15 degree Celsius. By the applying exergy equation, the theoretical amount of work that can be obtained from this transition can be calculated as:

$$W_{max} = Ex_{m,ph,LNG,in} - Ex_{m,ph,NG,out}$$

$$W_{max} = \dot{m}[(H_{in} - H_{out}) - T_0(S_{in} - S_{out})]$$

Assuming that LNG consists of methane, ethane, propane and butane at 87%, 9%, 3% and 1% by mole respectively, the theoretical amount of work can be calculated from the enthalpy values by simulation model software (ASPEN). The amount of exergy that can utilise in each alternative is represented in Figure 4.13 and 4.14.

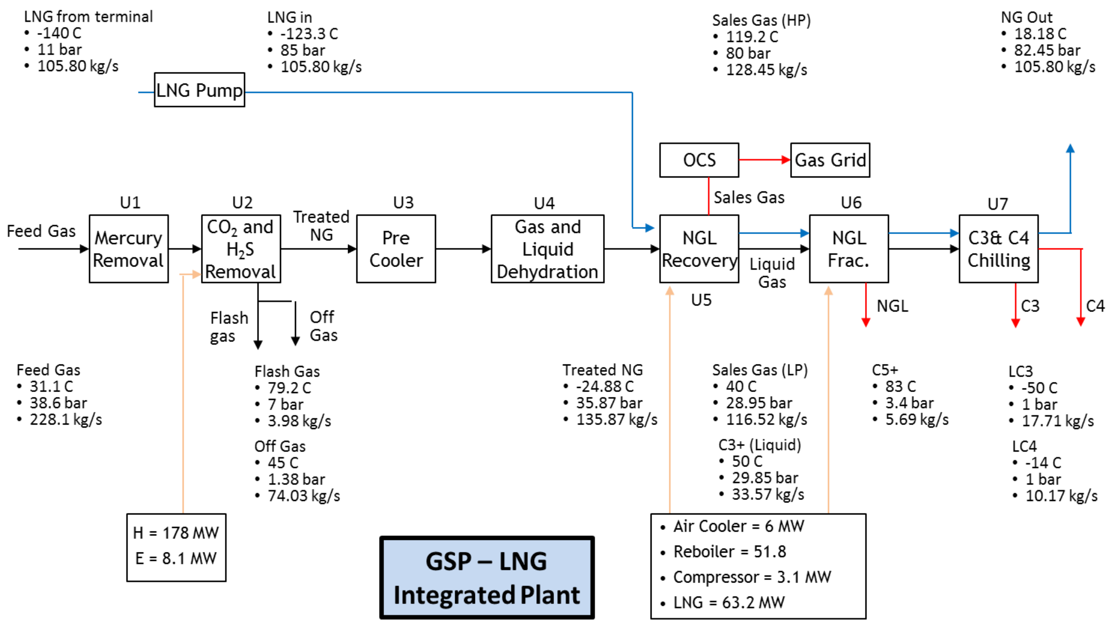

Figure 4.13: Schematic diagram of GSP=LNG Integrated Plant

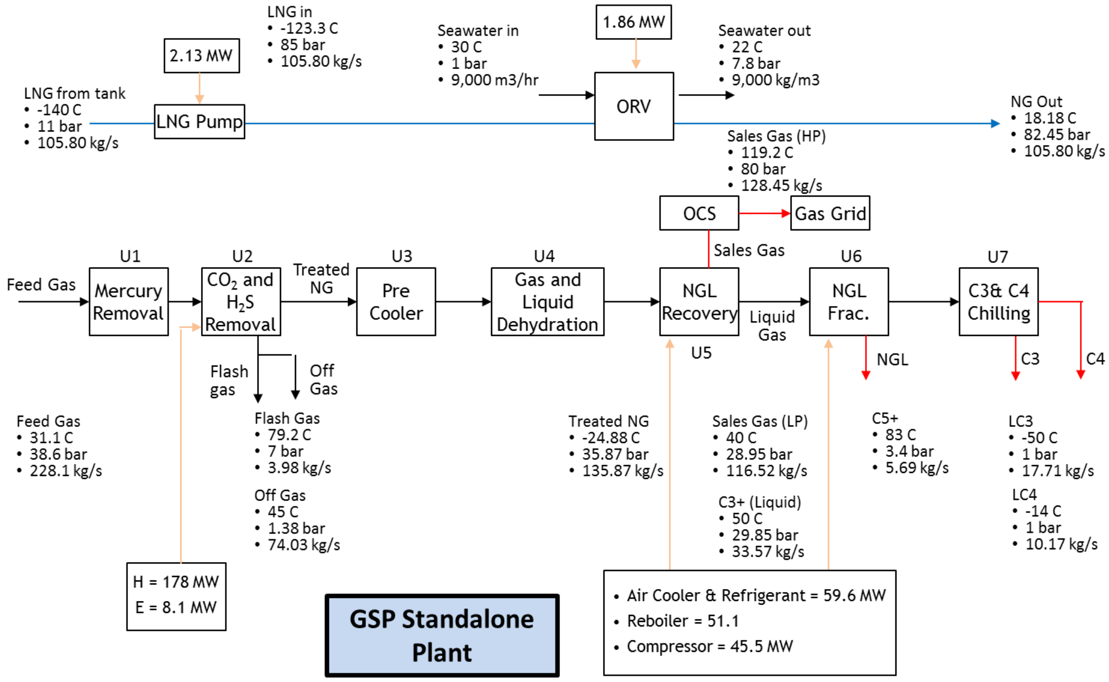

Figure 4.14: Schematic diagram of GSP and LNG Terminal Standalone

The overall exergy loss is defined as the exergy amount of the feedstock minus the exergy amount of the product. In this study, the exergy amounts of feedstocks are equal to the exergy of LNG, feed gas, seawater, heat input and electrical input. The exergy amount of products are natural gas from LNG, natural gas from feedstock, liquid propane, liquid butane and condensate (C5+), flash gas, off gas and seawater. At reference condition T_0 and P_0 at 30 degree Celsius and 1 atm, respectively, exergy loss from both system can be calculated and compare as shown in Figure 4.15.

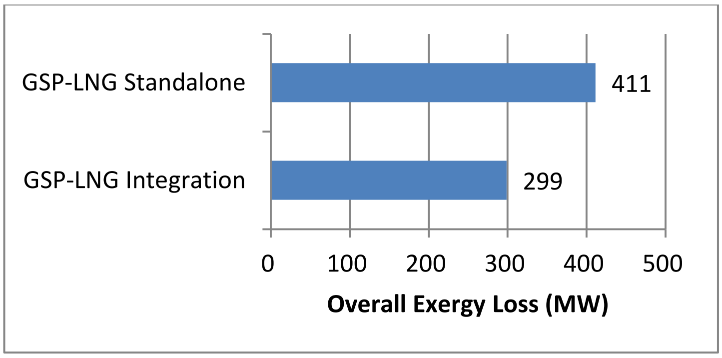

Figure 4.15: Results of the exergy analysis

Figure 4.15 makes clear that the GSP-LNG Integration is preferred, since it generates exergy loss less than the standalone case around 27% by the application of LNG cold into the process.

4.1.4 Risk Analysis

Risk analysis and management on the GSP-LNG Plant is performed and project risks are analysed and identified. From the project objectives and key success factors which have already identified, overall risk assessment chart or GSP-LNG Plant operation is constructed, as shown in Figure 4.16.

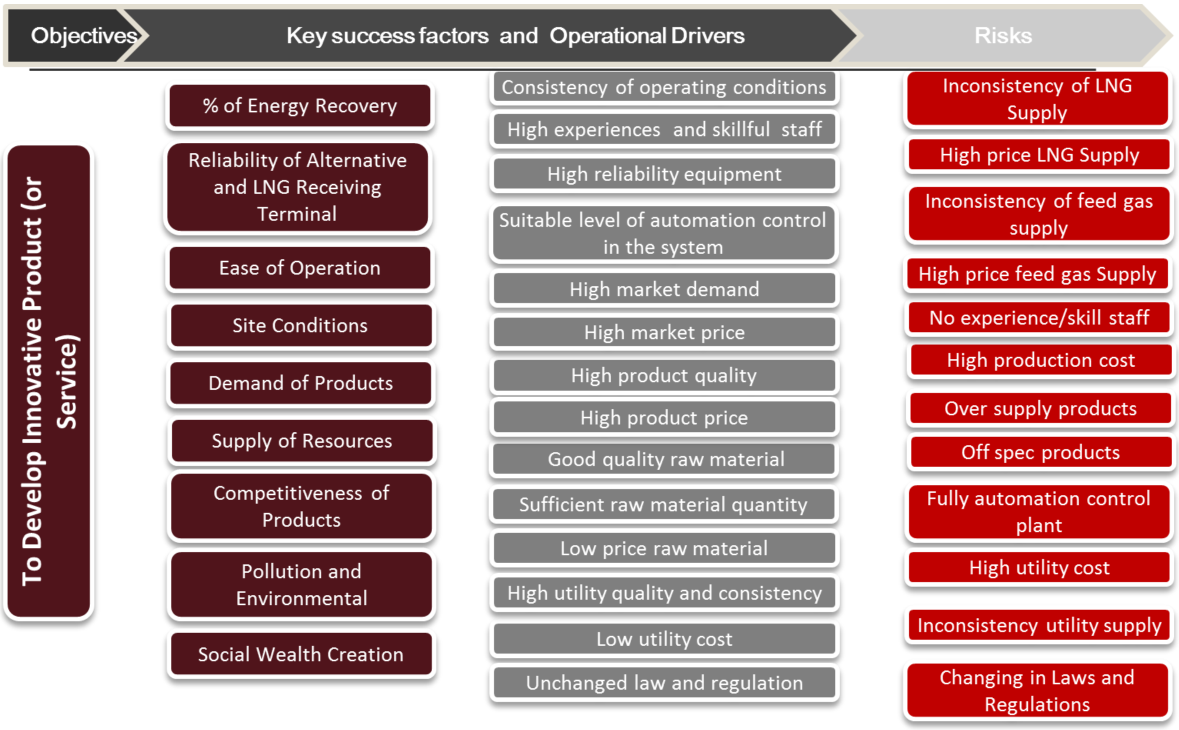

Figure 4.16: Risk assessment and risk identification

When analysed under the concept of impact and likelihood criteria, in the short term, most of the risk can be mitigated by well management operation plan and market supply contract but for long term, risk on the consistency of feed gas supply will have high degree of likelihood due to the statistical data that feed-gas in Gulf of Thailand are currently on the decline stage. Thus, when it comes to detail design stage of the project, breakeven of the GSP-LNG Plant and the projected feed gas supply from gulf of Thailand has to be seriously studied to confirm and ensure that the project will reach breakeven and generate certain amount of IRR before running out of feed gas.

4.2 Discussions

Results from study are categorised and discussed in order to clarify outcomes of the research in 2 main aspects which are:

1. Development of LNG cold utilisation technology assessment and prioritisation framework
2. A case study of LNG cold utilisation technology selection at Maptaphut LNG receiving terminal by the application of developed framework

4.2.1 Development of LNG Cold Utilisation Technology Assessment and Prioritisation Framework

LNG cold utilisation technology analysis framework is divided into 3 main parts which are:

1. Technology Portfolio to see the list of existing technologies as alternatives
2. Key Success Factors (KSFs) identification to identify what is the criteria on the LNG Cold Utilisation achievement.
3. Technology Prioritisation and Selection by Combination of Technology Screening, Analytical Hierarchy Process (AHP) and Technology Strategy Analysis (SWOT and GIDA Analysis)

4.2.1.1 LNG Cold Energy Utilisation Technology Portfolio

At the LNG receiving terminal LNG will be evaporated through vaporisers before being sent to natural gas pipeline network. During the evaporation process, LNG releases a large amount of cold energy (about 850 kJ/kg). The released LNG cold energy can be utilised through certain processes to enhance the economic performance of the whole terminal system. By this concept of utilising LNG cryogenic temperature benefit, LNG Cold Utilisation Technologies can be listed into technology portfolio, as shown in Figure 4.17.

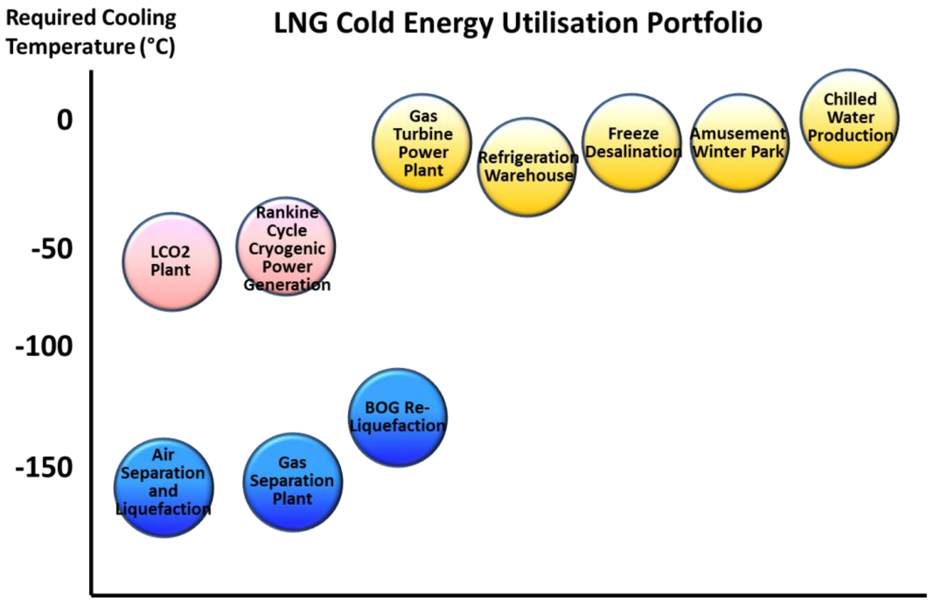

Figure 4.17: LNG Cold Utilisation Technologies Portfolio

As mentioned before that not only temperature benefit of LNG cold can be utilised but also pressure benefit as well. Another one (1) LNG cold utilisation technology is identified but categorised into pressure benefit application which are Direct Expansion of LNG through turbo expander to generate electrical.

In terms of available energy to be utilised by LNG cold, from thermodynamic view points, as required utilised temperature becomes lower, the advantage of LNG cold utilisation becomes larger. Thus LNG cold energy can be utilised more effectively at lower temperature (not higher than -100 degree Celsius). By this trend, if we see in the LNG cold utilisation portfolio, top two (2) of LNG cold utilisation option will be ASU-LNG integration and GSP-LNG integration.

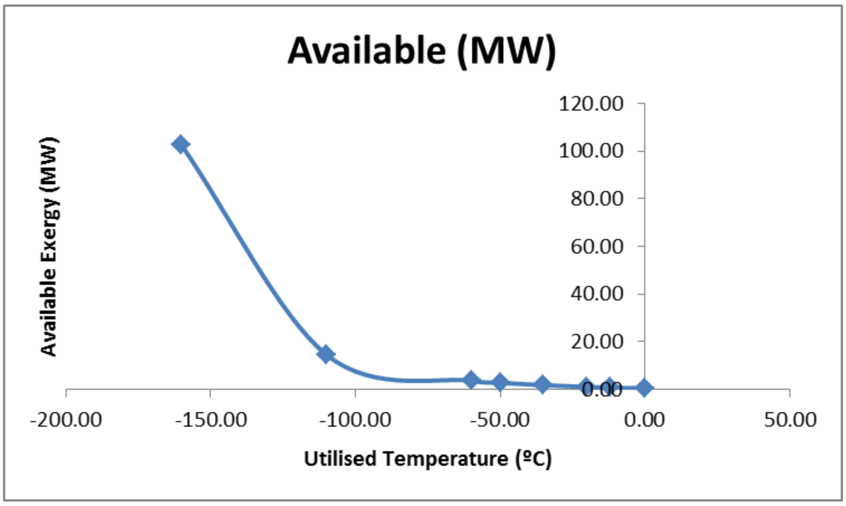

Figure 4.18: Available exergy of LNG cold at Maptaphut LNG receiving terminal (105.8 kg/s of LNG)

The relationship of available exergy and utilised temperature of Maptaphut terminal can be represent by the polynomial function of $y = 5E\text{-}07x^4 + 9E\text{-}05x^3 + 0.005x^2 + 0.0446x + 0.452$ where y is available exergy of LNG cold and x is the utilised temperature of LNG cold energy utilisation technology, as shown in Figure 4.18.

4.2.1.2 LNG Cold Energy Utilisation Technology Key Success Factors

Nine (9) Key Success Factors (KSFs) are logically identified as parameters to analyse each LNG cold utilisation alternative characteristic in order to perform the best systematic and reasonable factor for the prioritization process, the criteria and sub criteria with their definition have been identified as shown in Table 4.19.

These KSFs are identified based on 4 pillars of technology analysis, which are technological aspect, economical aspect, environmental aspect and social aspects in order to ensure that all stakeholders in the project are satisfied.

Table 4.19: KSFs of LNG Cold Utilisation

No.	KSFs	Definition of KSFs
1.	% of Energy Recovery (%ER)	How much energy benefit from LNG stream which LNG cold utilisation technique can be extracted as a sensible and latent heat by the principle of difference temperature and pressure
2.	Reliability of Alternative and	Since LNG cold utilisation require LNG stream

	LNG Receiving Terminal (RoA)	as a heat sink or coolant of the system, without LNG enters the system, the system will have an effect on its operating conditions and performance. LNG cold utilisation has to work as regasification unit for the terminal thus the system has to have high reliability to satisfy NG demand from customer which is the 1st priority function of terminal.
3.	Ease of Operation (EoO)	Complexity of the system and level of expert that require to operate the system
4.	Site Condition (SC)	LNG Cold Utilisation unit has to be nearby LNG terminal to reduce investment in high price LNG pipeline and the utilisation area has to be fit in with the availability land space near LNG terminal (~ 350 rai or 560,000 m^2, maximum distance is 2-3 km)
5.	Demand of Product (DoP)	Product that each LNG cold utilisation unit produce has to be on demand in the market or for terminal internal use

Table 4.19: KSFs of LNG Cold Utilisation (Cont')

No.	KSFs	Definition of KSFs
6.	Supply or Resources (SoR)	Availability of resources required to operate the system until get the finishing product. It can be explain and measure term of cost of commodity, availability, accessibility and sustainability.
7.	Competitiveness of Product (CoP)	Saving from the application of LNG cold (baht/kg of LNG) when compare to that system without LNG cold utilisation. Cost of product that each LNG cold utilisation produce has to be lower than the system without LNG in order to make

		competitive advantages
8.	Pollution and Environmental (PnE)	Low (and not excess the limit) CO_2 and VOCs emissions and other pollution which is generated from the system when each LNG cold utilisation is installed
9.	Social Wealth Creation (SWC)	The system generates positive effect on social around LNG receiving terminal and country, for example, job opportunity creation.

4.2.1.3 Technology prioritisation and selection by Combination of Technology Screening, Analytical Hierarchy Process (AHP) and Technology Strategy Analysis (SWOT and GIDA Analysis)

Technology screening method needed to be utilised to screen out un-potential technologies as a first filter in the system. If some un-potential technologies are not screened out, AHP matrixes will be too big and flooded with unnecessary data in the analysis process.

AHP application can give technology prioritisation result, but to conclude the technology selection process and make the option be ready of real operation and commercialisation, SWOT and GIDA analysis have to be applied in order to ensure the technology strategic point of view. After internal and external analysis (SWOT) of the project are analysed and project directions are identified by GIDA analysis, final result from this step would be the best alternative which can fulfil both technological and economical values of the project.

4.2.2 A case study of LNG cold utilisation technology selection at Maptaphut LNG receiving terminal by the application of developed framework

1. Technology selection from AHP result and Exergy Result by SWOT and GIDA Analysis.
2. Technical and economical feasibility analysis on the selected technology

4.2.2.1 Technology selection from AHP result and Exergy Result by SWOT and GIDA Analysis

As mentioned above, eleven (11) LNG cold utilisation technologies were initially listed in the portfolio as possible LNG cold energy utilisation technologies to be installed at LNG receiving terminal. After key success factors of the technology are identified, being screened with technology assessment criteria which was designed to balance technological, economical, environmental and social aspects, it was found that only four (4) LNG cold energy utilisation technologies, which are (1) Air Separation and Liquefaction, (2) Rankine Cycle Cryogenic Power Generation, (3) Liquefaction/Solidification of Carbon Dioxide, and (4) Chill Water Production were the possible technologies to be applied at Maptaphut LNG receiving terminal in Thailand.

With the AHP application, the expert opinions from both business and non-business sectors indicated the same direction that air separation and liquefaction plant were the best alternatives to be utilised as LNG cold energy utilisation technology at Maptaphut LNG receiving terminal. Even though the two groups of experts gave different weightings for the criteria, as shown in Figure 4.19, but for the conclusion in composite weight of the different LNG cold utilisation technologies against criteria weight, the result presented the same direction that air separation and liquefaction were the best alternatives, as shown in Figure 4.20. This was because the air separation and liquefaction alternative could satisfy all 4 main criteria, technological, economical, environmental and social aspect of the project. The utilisation of these technologies at the terminal would allow the highest LNG cold energy recovery rate among other alternatives, and would reduce the energy consumption at the terminal, which would result in the positive environmental and greenhouse gas impact. Social wealth could be created through the job opportunity required for the operation and maintenance of this new plant.

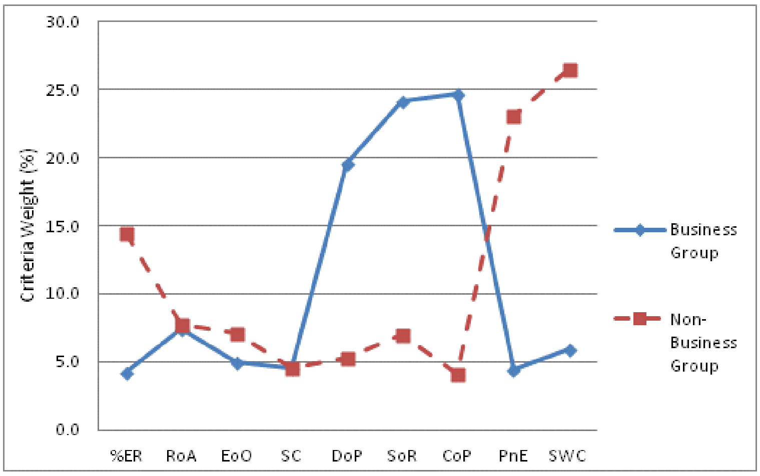

Figure 4.19: Comparison of criteria weight between business and non-business groups

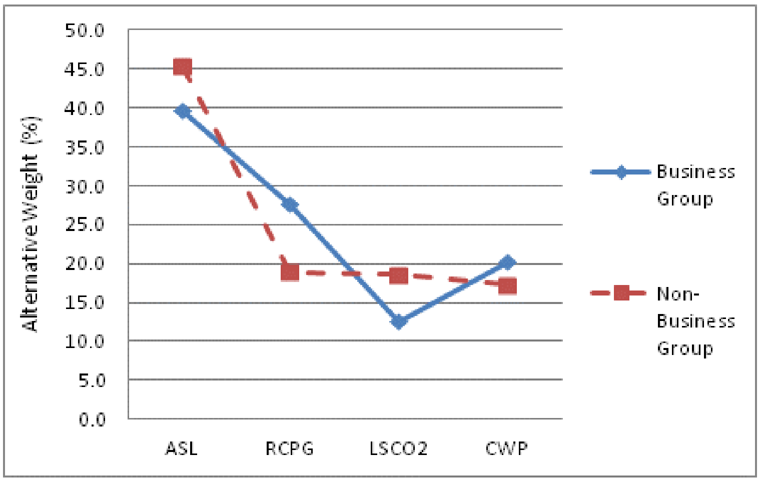

Figure 4.20: Comparison of alternative weight between business group and non-business groups

Air Separation and Liquefaction is the best choice because it has high value in most criteria. Rankine Cycle Cryogenic Power Generation has less favourable when compare to ASU choice due to it high technological value but a little bit low utilised temperature level which in turn gives only a moderate economic value.

Carbon Dioxide Liquefaction/Solidification is not selected because of high transportation cost of raw material (CO2). Chilled Water Production is also not chosen because of very low percentage of LNG cold energy recovery.

Top two (2) results from AHP and exergy analysis are ASU-LNG integration and GSP-LNG Integration. Based on technology strategy framework by analysing internal and external analysis of top 2 LNG cold utilisation technologies which have highest energy recovery potential (lowest utilisation temperature level), ASU-LNG integration plant and GSP-LNG integration plant is selected to analyse and compare against each other.

By the analysis, GSP-LNG integration plant is fit in the technology strategy of PTT than ASU-LNG integration choice. This is because GSP technology and knowhow is PTT expertise and business core competencies while ASU technology is not PTT business and expertise. In terms of products from the plant, GSP-LNG option produce natural gas and LPG which has higher demand in Thailand market than ASU-LNG option which produces industrial gases (Liquid N2, Liquid O2 and Liquid Ar).

4.2.2.2 Technical and economical feasibility analysis on the selected technology

The selected technology, GSP-LNG terminal plant, is technically feasible. The integrated plant provides the LNG terminal to operate in the base load mode of LNG regasification and enable GSP to extract propane and butane from feed-gas by the utilisation of LNG cold to reduce energy consumption and investment on the project.

Integrated plant design balances the LNG cold utilisation rate at 2.8 MTPA LNG per 650 MMscfd of feed gas to GSP. Once the integrated complex is in operation there will a LNG send out capacity of 1.5 MTPA in the 1st year of operation and increase to 3, 5, 6 and 10 MTPA in the 2nd, 4th, 5th and 10th years of operation, respectively, due to currently LNG import plan. By this designed technical and LNG import condition, balancing of imported LNG and feed gas separation process form the Gulf of Thailand is perfectly well balance as shown in Table 4.12.

In term of energy consumption, the benefit of the integration manifests itself in the gas plants by a lower requirement of compression power in the integrated case. This is a direct result of low temperature LNG cold utilisation, which allows the separation process to operate at a higher pressure thereby reducing the power for sales gas compression. Additional, a propane refrigerant compressor, which is required in the standalone GSP, can be deleted with the availability of cold LNG which reduces both operating cost and investment cost of the plant.

In terms of environmental concern, both GSP and LNG terminal operation points of view have a positive effect on the environmental emissions. On GSP, side the reduced need for compression energy will result in reduced fuel gas consumption and thus saving on operational expenditure of the integrated plant. On the LNG Receiving Terminal side, the benefits is expressed in a reduction of seawater pump energy, less seawater will need to be pumped into vaporiser units which give a contribution to the fuel gas saving and subsequent positive effect on environmental emissions.

Due to the energy and investment savings from the GSP-LNG integration plant when compare to the GSP-LNG standalone plant, estimation of saving can be demonstrated in the financial term of present value at 490.3 million USD on 20 years project life cycle.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

5.1. Conclusion

In the conclusion, I summarise my study in orderly sections from problem formulation, literature review summary, research methodology construction, application of scientific and management tools to final results of the study.

5.1.1 Background Information

LNG is imported to Thailand to secure the sustainable and ensure sufficient energy supply of the country by PTT Public Company Limited. In order to utilise LNG, which is a liquid form of natural gas, LNG receiving terminal is constructed to store LNG and transform it from liquid phase at minus 163 degrees Celsius to the required condition of natural gas grid network supply to end-users at the condition of 15 degree Celsius, gas phase. This is called regasification process where, in general process, LNG cold is wasted into seawater that is normally pumped through LNG evaporator to boil LNG without adding any value on this significantly LNG low temperature.

From LNG imported plan, 1.5 MTPA of LNG has been imported and target to reach 10 MTPA imported LNG in 2013, this means if we still use the normal regasification process with seawater run through LNG vaporisers, we will waste this estimated energy benefit of LNG cold utilisation of 850 kJ/kg, which is around 9,500 TJ or 202 ktoe per year of total 10 MTPA LNG.

5.1.2 Problem Formulation

Rationale of the issue is categorise into 2 aspects: first, economical aspect, when we purchase LNG we pay for the cost of natural gas, and cost of liquefaction, which is LNG cold, so when we use it, we should not just waste it into environmental without any beneficial generation. Second aspect, energy efficiency, we put energy into liquefaction process to minimise natural gas density for transportation purpose by cooling it down to cryogenic temperature, this input energy should not be just wasted into the surrounding without any value creation.

By this situation, we are clearly aware that we should harvest and recover this LNG cold energy back from regasification process but what and how should we do to appropriately do it. This lead to the problem formulation of “What is the Best LNG Cold

Utilisation Technologies for LNG Regasification Process at Maptaphut LNG Receiving Terminal". The best solution to this should offer both System Economical Feasibility and High Energy Efficiency to the terminal and social.

5.1.3 Research Objectives

According to the problem statement, the purpose of this study is to identify the best LNG cold energy utilisation technique for Maptaphut LNG receiving terminal and bring the stakeholders attention to the benefits obtainable through the utilisation of LNG cold energy in terms of energy saving and environmental safety. Clear objectives of the study are identified as follows:

- To answer whether LNG cold energy utilisation concept is suitable and feasible for LNG receiving terminal or not
- To identify what is the key success factors for LNG cold utilisation application which optimise value in both technical and non-technical aspects
- To develop LNG Cold Utilisation Technology Analysis and Prioritisation method
- To test the key success factors effectiveness and LNG Cold Utilisation Technology Analysis and Prioritisation framework by utilising them on the case study at Maptaphut LNG receiving terminal
- To verify the case study result by elaboration of feasibility study on both technological and economical aspects.
- To increase awareness of LNG terminal owner on the LNG cold energy utilisation on the benefit of LNG cold.

5.1.4 Literature Review Summary

As a good start of research methodology formulation, literature review topics are scoped into 3 main areas in order to construct the infrastructure knowledge of the research that will lead to the appropriate methodology structure and accurate study result.

Table 5.1: Literature review summary

Literature Review Topics	Summary	References
1. How much energy can we save by LNG cold utilisation?	• Maximum of 42 MW from 1.5 MTPA LNG is available to be saved at 1st phase terminal and increase to 280 MW in 2nd phase terminal at 10 MTPA LNG	[1], [9], [11], [14], [23]

Table 5.1: Literature review summary (Cont')

Literature Review Topics	Summary	References
2. What do people do to this all around the world?	• LNG cold energy utilisation concept is to use LNG vaporiser unit as a heat sink for other process • 9 main types of LNG cold utilisation methods are existing all around the world e.g., LNG cold integration with air separation plant, cryogenic power plant, refrigeration warehouse and etc. • The application are exiting and in operation at some LNG receiving terminal for example in Japan, Korea and Taiwan. Integration with air separation and liquefaction plant is the highest choice application.	[1-4], [11-17], [24-25], [28-32]
3. How do we know that the selected option is the best option?	• How best of LNG cold energy utilised facility depends on both technical and non-technical aspects. This kind of problem can be considered as a multi-criteria decision making problem. Thus AHP which is widely used to assist this type of problem is the appropriate tool to ensure that the result will be the most reasonably best option. • AHP is scientific method multi criteria decision making tools which its application on many outstanding works in many fields have been published in international journals	[5-6], [8], [10], [18], [19-20],

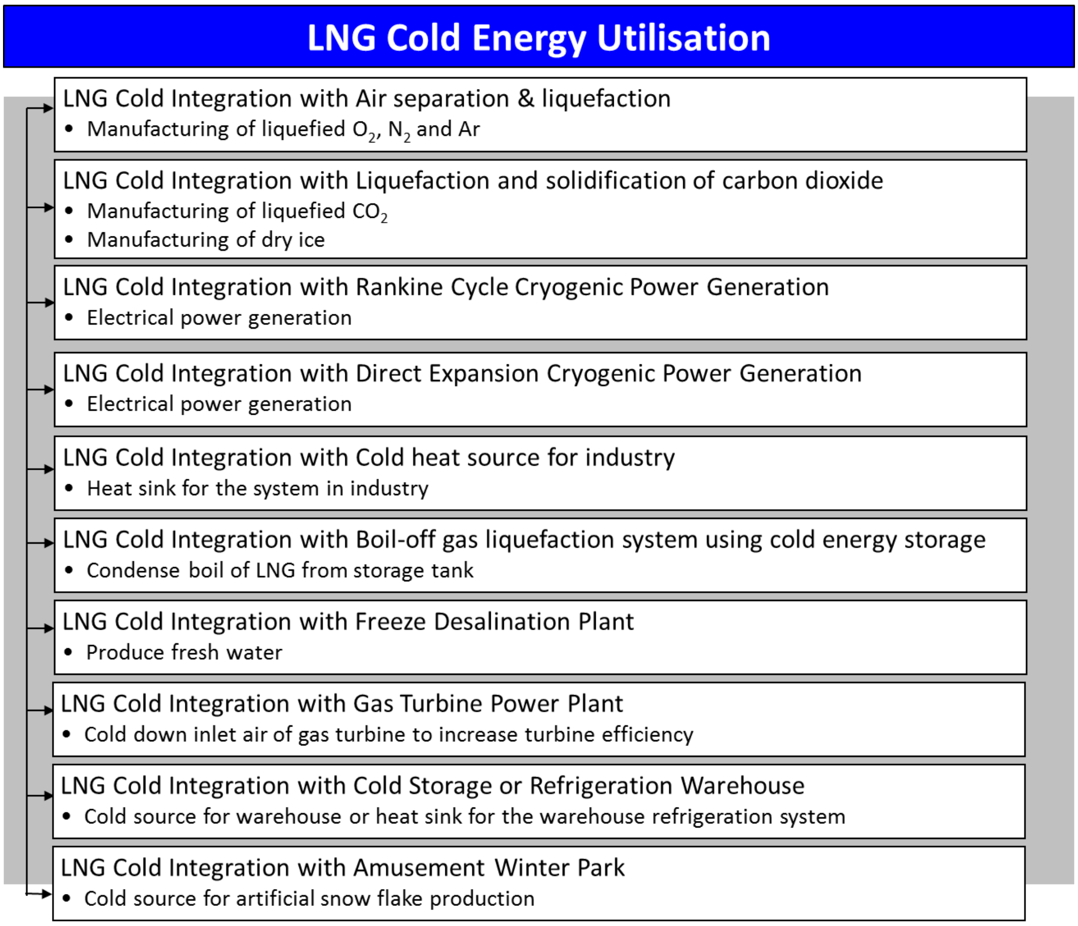

Figure 5.1: List of LNG cold energy utilisations

5.1.5 Research Methodology Formulation

By the combination of scientific and business strategy method approaches in this study, research methodology is constructed into 7 steps to achieve the final results of the study.

Table 5.2: Research methodology Summary

Step	Methodology	Methodology Purpose	Expected Results
1	Technology Portfolio	Identify LNG cold energy utilisation from all reliable sources by appropriate acquisition method. (Section 3.3.1)	List of technology which is available all over the world.
2	Key Success Factors Identification	Identify key success factor of the LNG cold energy utilisation application by the application of critical success factors concept theory. (Section 3.3.2)	List of LNG cold energy utilisation key success factors.

Table 5.2: Research methodology Summary (Cont')

Step	Methodology	Methodology Purpose	Expected Results
3	Technology Screening Method	Screen out un-feasible technologies from the portfolio by the application of limitation of technology application framework. (Section 3.3.3)	List of potential LNG cold energy utilisation technologies at Maptaphut terminal.
4	Technology Prioritisation	Prioritise technology by the application of multi-criteria decision making tools, AHP method (Section 3.3.4)	Top priority technologies in series.
5	Technology Strategy Development	Identify the best option of technology under current business environmental and constraints by the application of internal and external factor analysis concept (SWOT and GIDA analysis) (Section 3.3.5)	Final selection of the technology which have a balancing on energy, economic, social and environmental aspects also fulfil investor need by showing the best strategic alignment potential.
6	Thermodynamic Analysis	Calculate the estimated energy saving potential from the selected technology by the application of 1st and 2nd laws of thermodynamic theory (Section 3.3.6)	Estimated energy and exergy saving on the select LNG cold energy utilisation option.
7	Economic Analysis	Project the economic benefit of the selected technology by the application of cash flow analysis concept (Section 3.3.7)	Estimated money saving on the select LNG cold energy utilisation option.

5.1.6 LNG Cold Utilisation Technology Analysis and Selection Framework

The framework is developed as 3 steps guideline for the selection of LNG cold energy utilisation technology as shown in Figure 5.2. First step, LNG cold utilisation technology portfolio has been identified as the list of available technology alternatives. In the second step, technology screening concept will be applied to screen out low potential technologies by the screening criteria based on performance and structural limits concept.

For the third step, the combination of multi-criteria decision making tools (AHP) and technology strategy analysis (SWOT and GIDA) are applied on the potential technologies in order to priorities technologies and select the best LNG cold utilisation technology.

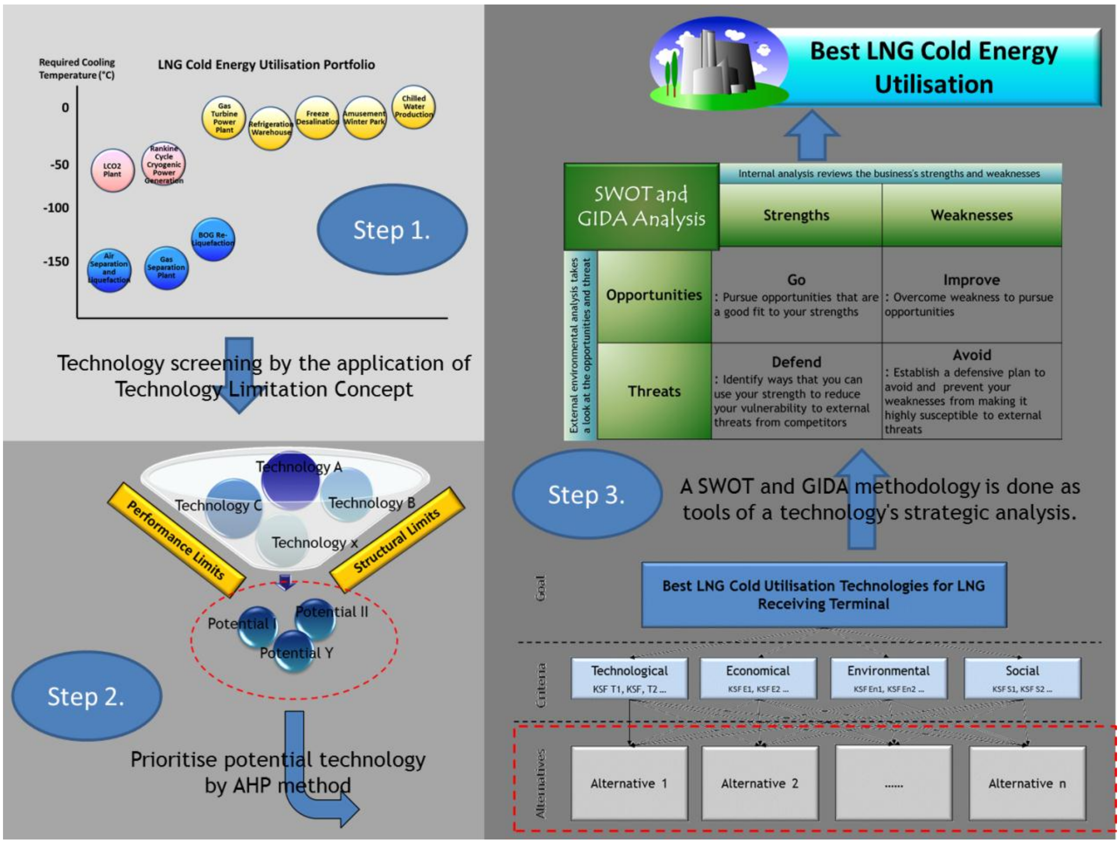

Figure 5.2: LNG Cold Utilisation Technology Selection Framework

5.1.7 A Case Study of LNG Cold Utilisation Technology Analysis and Selection Framework on Maptaphut LNG Receiving Terminal

5.1.7.1 LNG Cold Energy Utilisation Portfolio

LNG cold energy utilisation portfolio is listed and plotted by their required cooling temperature on each application as shown in Figure 5.3.

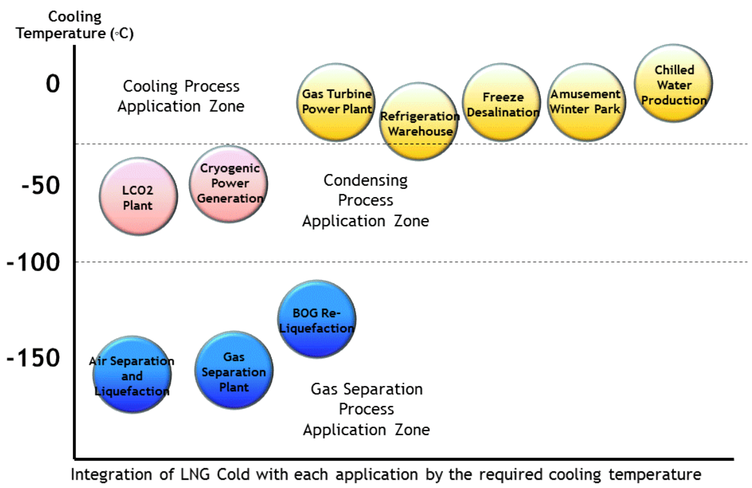

Figure 5.3: Integration of LNG Cold with each application by the required cooling temperature (Cooling temperature of each application can be varied base-on the designed pressure level of each process)

By the limitation of site specific constraints and high send-out pressure requirement of natural gas to gas grid at Maptaphut LNG receiving terminal, some LNG cold utilisation options in portfolio are screened out, only 4 options are available as potential alternative which are (1) Air separation and liquefaction, (2) Cryogenic power generation, (3) LCO2 liquefaction and (4) Chilled water production.

5.1.7.2 Expert Opinion Analysis on Analytical Hierarchy Process

Nine (9) key success factors of LNG cold energy utilisation are identified and assigned as AHP criteria in the AHP structure to prioritise 4 (four) potential LNG cold energy utilisation alternatives. Expert opinions from business and non-business sectors are selected to be interviewed. Interestingly AHP result to show that even though expert from non-business sector gave high score on the energy and environmental related factors and business sector gave high score on market related factors but the top priority result is the same which are air separation and liquefaction option. This is because LNG cold integration with air separation and liquefaction option generates high value in energy, market, environmental and social factors.

5.1.7.3 Exergy Analysis of LNG Cold Energy Utilisation Portfolio

From the thermodynamic analysis of LNG cold exergy shows that the benefit of LNG cold drastically decrease when utilising temperature reduces from -160 degree Celsius to -100 degree Celsius. Matching this temperature trend with cooling temperature required in each LNG cold utilisation option, this can conclude that only ASU-LNG

Integration and GSP-LNG Integration are worth doing for LNG cold energy utilisation if focusing only on thermodynamic benefits.

For the other options of LNG cold energy utilisation technology, which has an utilised temperature high than -100 degree Celsius, there is not much difference in term of thermodynamic benefit. If those choices of LNG cold energy utilisation will be selected, energy recovery issue can be negligible, other factors such as business and operational concern factors would only be taken into account for their selection process.

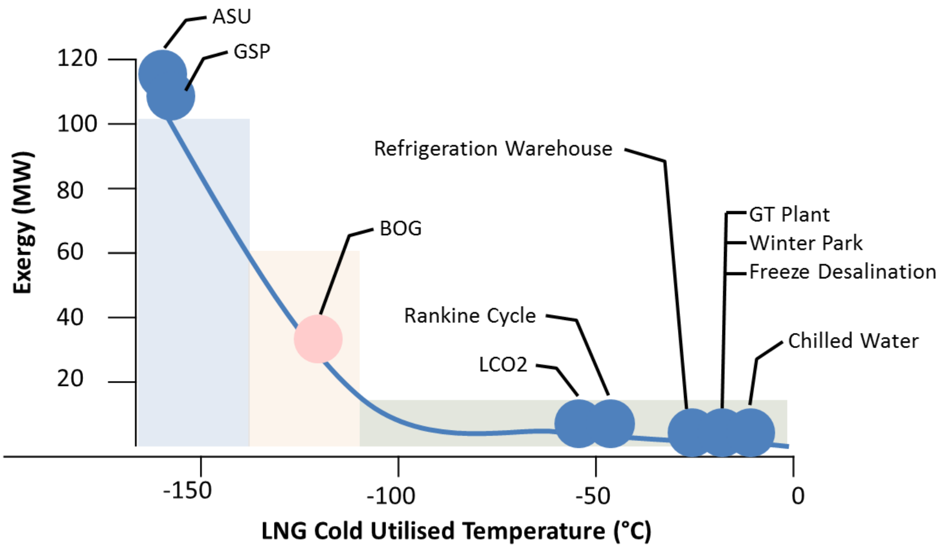

Figure 5.4: Relationship between available exergy of LNG cold and utilised temperature of LNG cold integration (LNG capacity at 2.8 MTPA)

5.1.7.4 LNG Cold Energy Utilisation Technology Selection for Maptaphut LNG Receiving Terminal

To ensure that the best option will be selected, exergy analysis result and AHP result are combined and evaluated together. GSP-LNG integration option is taken back from screen method into account for consideration by it high exergy benefit. It was screened out by the reason of unavailable GSP nearby at the present, but there is an opportunity to be constructed new GSP nearby LNG terminal in the future since raw natural gas (feed gas) from gulf of Thailand is still over supply on the existing PTT GSPs capacity.

ASU-LNG integration and GSP-LNG integration are analysed against each other by the technology strategy analysis and development framework. Results from SWOT and GIDA analysis shows that LNG cold energy utilisation, which target to be applied at

Maptaphut LNG receiving terminal, is suggested to be the option of GSP-LNG integration plant. This selected option shows the balance in both technical and non-technical aspects of the project while offers high exergy benefit.

In terms of business strategy, since LNG receiving terminal is owned and operated by PTT group and GSP is also owned by PTT group. It is considered to be a core competency business of PTT group, thus integration of GSP and LNG plant together is a fully strategy business alignment and synergetic resources.

5.1.7.5 Thermodynamic Analysis of GSP-LNG Integration Plant and Saving Against GSP-LNG Stand Alone Plant

The integration plant is technically feasible provided the LNG terminal operates in the base load mode to ensure constant supply of natural gas to natural gas network. The GSP with LNG cold utilisation is designed to extract propane and butane, which is LPG product from feed gas. Ratio of LNG and feed gas to GSP in the LNG cold integration scheme is 1:2.2 (kg LNG: kg feed gas).

In terms of energy efficiency, the GSP-LNG integrated plant can save energy around 42 MW of electrical when compared to the standalone GSP plants. This is because of a lower requirement of compression power in the integrated case which is a direct result of the low temperature of the LNG. By this efficient used of energy, the integration plant in turn have a positive effect on the environmental emission by a reduced energy consumption of the system. Exergy analysis clearly demonstrate that GSP-LNG integration plant generate exergy loss less than in GSP LNG Standalone plant around 27%.

Saving on CAPEX and OPEX of the integrated system against standalone option is around 490 million USD on 20 years project life cycle present value basis.

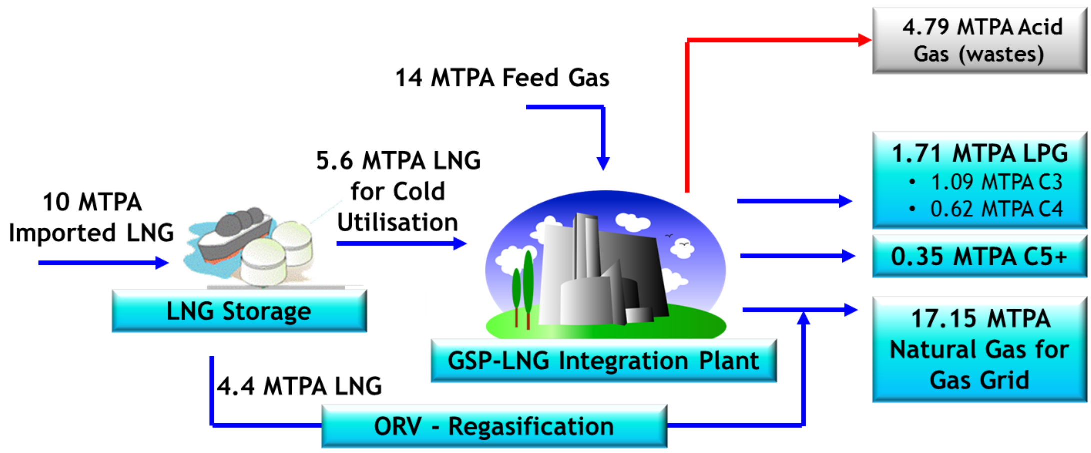

Figure 5.5: Mass Balance of Proposed GSP-LNG Plant Integration at Maptaphut LNG Receiving Terminal

5.1.8 Lessons Learnt from the Study

5.1.8.1 Screen Out Alternative from Technology Screening Method should be Re-Checked

One of the noteworthy lessons learnt from the study is on the technology prioritisation and selection process. First one is on the application of technology screening concept. We will see in the case study section that from the screening result, GSP-LNG option has already been screened out by the reason that there is no existing Gas Separation Plant (GSP) around the terminal area. However, when come to the final result GSP-LNG plant is selected to be the best alternative for Maptaphut LNG receiving terminal by the application of technology strategy analysis. By this lesson, when apply the technology screening concept on the screening process, the screened-out technology should be re-evaluated again one more time after prioritisation process to confirm that we don't miss the potential option on the very early stage.

5.1.8.2 Appropriate Numbers of Criteria and Alternative on AHP Structure have an Impact on Level of Concentration of Expert on Expert Opinion Interview

Another lesson is on the AHP application. We learnt that number of criteria and number of alternatives in AHP structure have direct effect on how big is the matrixes of AHP evaluation process. This mean on the pair-wise comparison process where experts give their opinion on AHP evaluation process, the experts have to deal with a very large amount of pair wise comparison scoring process. For example, as show in Figure 5.6, if AHP structure consists of 7 criteria and 15 alternatives, expert have to score the value on pair wise comparison for 756 time. This is not practical on the expert opinion interview process. By this lesson learnt, if you will use AHP as a tool on your multi criteria decision making process, numbers of criteria and alternative have to be minimised to eliminate massive scoring process which generate fatigue and less concentration on the scoring quality during expert interview process.

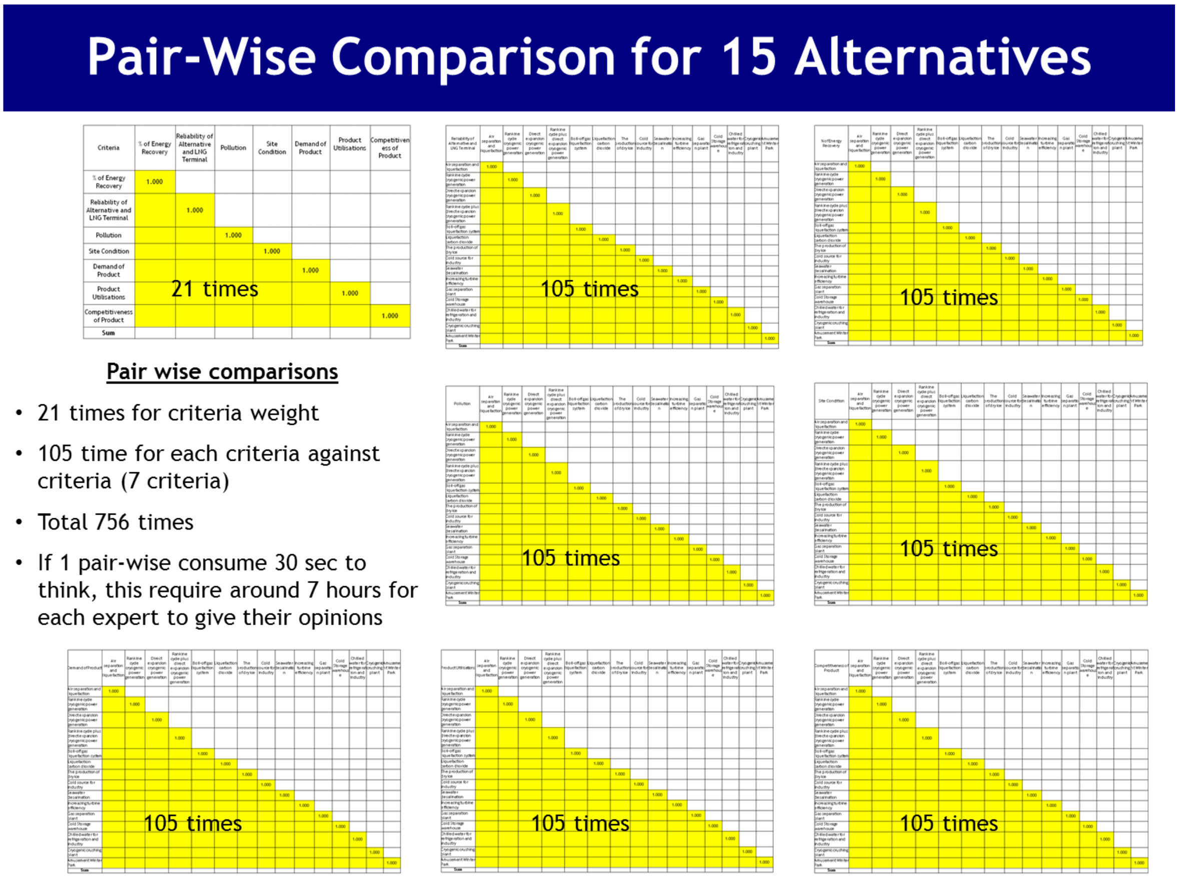

Figure 5.6: Large number of criteria and alternative on AHP structure results in massive number of required pair-wise comparison scoring from experts.

5.1.8.3 Selection of Expert Groups from Different Professionals have High Impact on AHP Criteria Weight and Results

The AHP results show that a person who belongs to different organisations and working environments tends to have different interests and opinion as shown in Figure 5.7. It is good for AHP analysis that we will be able to acquire different opinions to cover all area of stakeholders. For this study, it is lucky for us that there is a different weight criteria results from different expert groups but the final ranking result of alternative is the same. This is a suggestion for further application, if the different criteria weight results lead to different ranking alternative priorities in each group, you might need to apply AHP method to find the priority of each expert group on the project to find the conclusion.

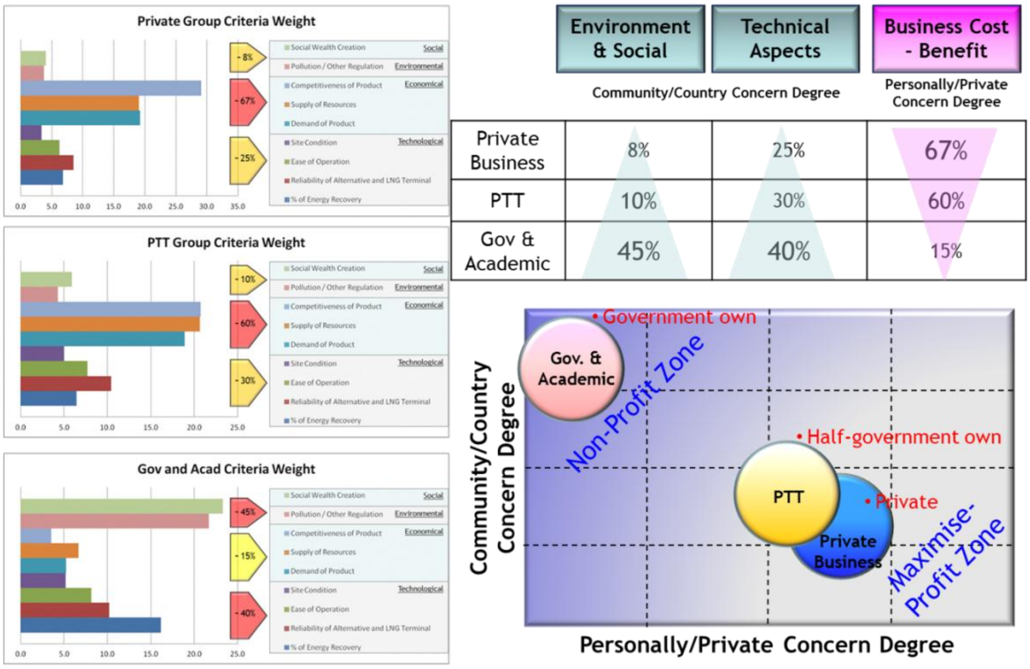

Figure 5.7: Differences of AHP Criteria Weight Result on each Type of Expert Groups.

5.2. Future Work

From the proposed designed system, we see that there is still surplus amount of LNG between cold demand and import capacity. This result in the saving from GSP-LNG integrated plant is 0.0123 USD/kg of cold utilised LNG and 0.009 USD/kg of imported LNG which mean there is cold exergy available for utilising.

Looking at Figure 4.14, Compressor unit in the OCS (Operating Centre System) of natural gas pipeline network which is required to increase sales gas pressure from GSP is another potential heat source of energy which would be possible to be integrated into the LNG cold energy utilisation technique in the future. Using LNG cold to cool down inlet gas and compressed gas has a potential to reduced need for compression energy will result in reduced fuel gas consumption and thus saving on operational expenditure. Design the heat recovery unit to use compressed natural gas as a heat source and use LNG as a heat sink in the system would be a future study to harvest surplus LNG cold exergy which is still available after the application of GSP-LNG integration plant.

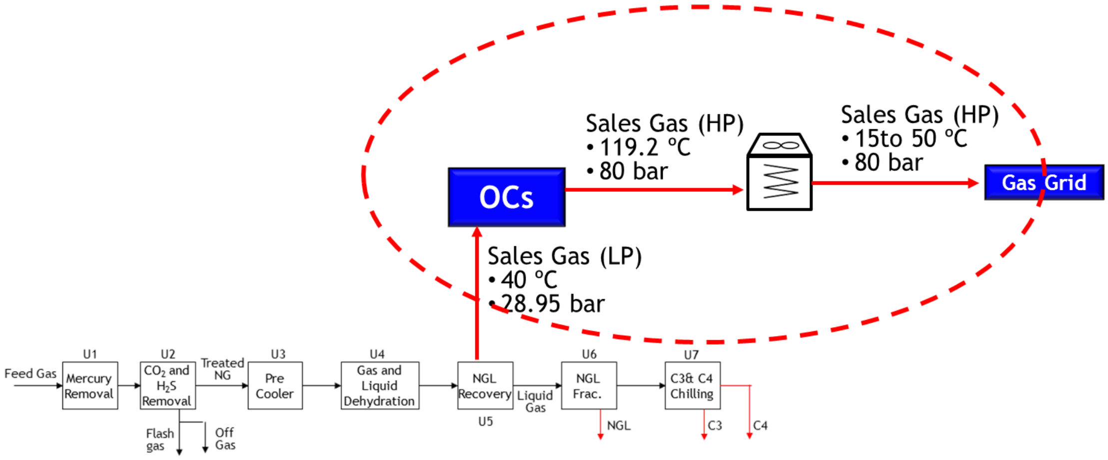

Figure 5.8: Required heat sink on compression process at OCs before discharge natural gas into gas grid is potentially the other application of LNG cold utilisation

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APPENDIXES

Appendix A

The data of pair-wise comparison of the different technologies with respect to each criteria from business group (interviewed from 7 experts) that was analyzed in the LNG cold energy utilization technology selection.

Table A1: Pair-wise comparison of the different technologies with respect to percent of energy recovery criteria (ER)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	5	4	8	0.597
RCPG	1/5	1	1/2	4	0.140
LSCO2	1/4	2	1	5	0.214
CWP	1/8	1/4	1/5	1	0.050

Table A2: Pair-wise comparison of the different technologies with respect to reliability of alternative and LNG terminal criteria (RoA)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/4	1/2	1/4	0.089
RCPG	4	1	2	1/2	0.295
LSCO2	2	1/2	1	1/3	0.157
CWP	4	2	3	1	0.460

Table A3: Pair-wise comparison of the different technologies with respect to ease of operation criteria (EoO)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/4	1/3	1/5	0.073
RCPG	4	1	3	1/2	0.310
LSCO2	3	1/3	1	1/3	0.156
CWP	5	2	3	1	0.461

Table A4: Pair-wise comparison of the different technologies with respect to percent of site condition criteria (SC)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/5	1/3	1/7	0.057
RCPG	5	1	3	1/3	0.263
LSCO2	3	1/3	1	1/5	0.122
CWP	7	3	5	1	0.558

Table A5: Pair-wise comparison of the different technologies with respect to demand of product criteria (DoP)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/5	4	1/3	0.134
RCPG	5	1	8	3	0.567
LSCO2	1/4	1/8	1	1/4	0.054
CWP	3	1/3	4	1	0.245

Table A6: Pair-wise comparison of the different technologies with respect to supply of resources criteria (SoR)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	2	8	3	0.488
RCPG	1/2	1	7	1	0.256
LSCO2	1/8	1/7	1	1/5	0.046
CWP	1/3	1	5	1	0.210

Table A7: Pair-wise comparison of the different technologies with respect to percent of competitiveness of product criteria (CoP)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	5	5	9	0.622
RCPG	1/5	1	1/2	4	0.135
LSCO2	1/5	2	1	5	0.197
CWP	1/9	1/4	1/5	1	0.047

Table A8: Pair-wise comparison of the different technologies with respect to reliability of pollution and environmental criteria (PnE)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	8	8	8	0.717
RCPG	1/8	1	1	2	0.109
LSCO2	1/8	1	1	2	0.109
CWP	1/8	1/2	1/2	1	0.066

Table A9: Pair-wise comparison of the different technologies with respect to reliability of social wealth creation criteria (SWC)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	3	2	8	0.504
RCPG	1/3	1	1/2	3	0.162
LSCO2	1/2	2	1	4	0.272
CWP	1/8	1/3	1/4	1	0.061

Appendix B

The data of pair-wise comparison of the different technologies with respect to each criteria from non-business group (interviewed from 7 experts) that was analyzed in the LNG cold energy utilization technology selection.

Table B1: Pair-wise comparison of the different technologies with respect to percent of energy recovery criteria (ER)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	5	4	8	0.592
RCPG	1/5	1	1/2	5	0.150
LSCO2	1/4	2	1	5	0.210
CWP	1/8	1/5	1/5	1	0.048

Table B2: Pair-wise comparison of the different technologies with respect to reliability of alternative and LNG terminal criteria (RoA)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/3	1/2	1/5	0.083
RCPG	3	1	3	1/3	0.257
LSCO2	2	1/3	1	1/4	0.128
CWP	5	3	4	1	0.532

Table B3: Pair-wise comparison of the different technologies with respect to ease of operation criteria (EoO)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/5	1/3	1/6	0.061
RCPG	5	1	3	1/3	0.268
LSCO2	3	1/3	1	1/5	0.125
CWP	6	3	5	1	0.546

Table B4: Pair-wise comparison of the different technologies with respect to percent of site condition criteria (SC)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/5	1/3	1/7	0.057
RCPG	5	1	3	1/3	0.263
LSCO2	3	1/3	1	1/5	0.122
CWP	7	3	5	1	0.558

Table B5: Pair-wise comparison of the different technologies with respect to demand of product criteria (DoP)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	1/5	5	1/3	0.147
RCPG	5	1	7	2	0.510
LSCO2	1/5	1/7	1	1/5	0.053
CWP	3	1/2	5	1	0.290

Table B6: Pair-wise comparison of the different technologies with respect to supply of resources criteria (SoR)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	3	8	2	0.492
RCPG	1/3	1	6	1	0.225
LSCO2	1/8	1/6	1	1/5	0.048
CWP	1/2	1	5	1	0.234

Table B7: Pair-wise comparison of the different technologies with respect to percent of competitiveness of product criteria (CoP)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	5	4	9	0.596
RCPG	1/5	1	1/2	5	0.144
LSCO2	1/4	2	1	6	0.217
CWP	1/9	1/5	1/6	1	0.043

Table B8: Pair-wise comparison of the different technologies with respect to reliability of pollution and environmental criteria (PnE)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	7	6	8	0.662
RCPG	1/7	1	1/2	3	0.112
LSCO2	1/6	2	1	4	0.172
CWP	1/8	1/3	1/4	1	0.054

Table B9: Pair-wise comparison of the different technologies with respect to reliability of social wealth creation criteria (SWC)

	ASL	RCPG	LSCO2	CWP	Relative Weight
ASL	1	4	2	7	0.504
RCPG	1/4	1	1/2	4	0.157
LSCO2	1/2	2	1	6	0.287
CWP	1/7	1/4	1/6	1	0.053

Appendix C

Maptaphut LNG receiving terminal which is chosen to be research case study has main specification as shown in table C1.

Table C1: Maptaphut LNG Terminal Specification

General LNG Receiving Terminal Specification	
LNG Tank	Full Container
LNG Vaporiser	Open Rack Vaporiser (ORV)
Number of Jetty	1
Maximum Ship Capacity (m3)	125,000 – 264,000
LNG Storage Tank Capacity (m3)	2 x 160,000
Production Capacity (million standard cubic foot per day)	700 mmscfd of send out natural gas or 5 MPTA of LNG unloading
Open Rack Vaporiser	4 + 1

Available area around Maptaphut LNG terminal which is potentially to be used within 3 km radius from LNG tank is identified as show in figure C1.

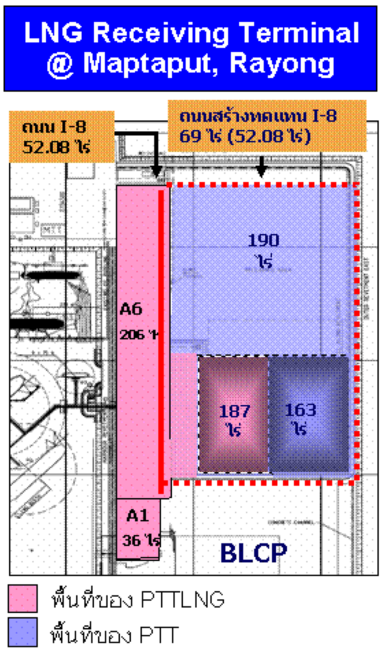

Figure C1: Available area around LNG Terminal