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Techno Economic Evaluation of Cold Energy from Malaysian Liquefied Natural Gas Regasification Terminals

Mohd Amin Abd Majid [1,*], Hamdan Haji Ya [1], Othman Mamat [1] and Shuhaimi Mahadzir [2]

1 Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Malaysia; hamdan.ya@utp.edu.my (H.H.Y.); drothman_mamat@utp.edu.my (O.M.)

2 Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Malaysia; shuham@utp.edu.my

* Correspondence: mamin_amajid@utp.edu.my

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Abstract: In order to cater for increased demand for natural gas (NG) by the industry, Malaysia is required to import liquid natural gas (LNG). This is done through PETRONAS GAS Sdn Bhd. For LNG regasification, two regasification terminals have been set up, one in Sungai Udang Melaka (RGTSU) and another at Pengerang Johor (RGTPJ). RGTSU started operation in 2013 while RGTPJ began operation in 2017. The capacities of RGTSU and RGTPJ are 3.8 (500 mmscfd) and 3.5 (490 mmscfd) MTPA, respectively. RGTSU is an offshore plant and uses an intermediate-fluid-vaporization (IFV) process for regasification. RGTPJ is an onshore plant and employs open-rack vaporization (ORV). It is known that a substantial amount of cold energy is released during the regasification process. However, neither plant captures the cold energy released during regasification. This techno economic study serves to evaluate the technical and economic feasibility of the cold energy available during regasification. It was estimated that approximately 47,214 and 88,383 kWh of cold energy could be generated daily at RGTPJ and RGTSU, respectively, during regasification processes. Converting this energy into RTh at 70% thermal efficiency, and taking the commercial rate of 0.549 Sen per RTh, for the 20-year project life, an internal rate of return (IRR) of up to 33% and 17% was estimated for RGTPJ and for RGTSU, respectively.

Keywords: liquefied natural gas; cold energy; regasification; chilled water; techno economic

1. Introduction

The share of the liquefied natural gas (LNG) international trade has grown continuously in recent years and LNG has become an important tool for gas security [1]. The traditional supply chain of LNG includes gas production, liquefaction, shipping, storage, and regasification. The practical way to transport natural gas (NG) across oceans is by liquefaction of NG to LNG [2]. This is done by cooling the NG to −162 °C at atmospheric pressure. The LNG is then regasified back to NG at import terminals [3]. Normally, during regasification, the cold energy during the regasification process is discarded. This is also true for LNG regasification terminals in Malaysia. The Malaysian economy grew at 5.51% for the period 2016–2017. Like many developing countries, economic growth has resulted in increased populations in urban areas as well as increased income per capita to catch up with higher living standards, all of which are driving the demand for energy. NG is one of the best choices of primary energy mixes to meet the growing energy demand in modern society due to its clean burning characteristic, high combustion efficiency, and low contribution to greenhouse gases emissions. It is estimated that NG contributes about 24% of Malaysia's energy requirements [4]. To meet the growing demand, Malaysia imports LNG from other producing countries. Currently, two LNG regasification terminals have been built by PETRONAS Gas. The first regasification terminal in Malaysia was set up in Sungai Udang, Melaka (RGTSU), and the second terminal was set up in Pengerang, Johor (RGTPJ). RGTSU started its operation in 2013, and RGTPJ began its operations in the fourth quarter of 2017 [5]. Both terminals are connected to Peninsular Gas Utilization grid pipelines, and then distributed to customers [6].

The RGTSU consists of floating storage and regasification units (FSRUs), and RGTPJ is an onshore terminal. The FSRU is a terminal LNG carrier that has been altered for regasification. Meanwhile, onshore terminals are usually located near the sea. These terminals have operating capacities of 3.8 (500 mmscfd) and 3.5 MTPA (490 mmscfd), respectively [7]. For vaporization, RGTSU employs intermediate fluid vaporization (IFV) technology whereas RGTPJ employs open-rack vaporization (ORV) technology. Table 1 summarizes the information on the terminals.

Table 1. Summary of terminals' information.

No	Item	RGTSU	RGTPJ
1	Facilities		
2	Jetty	Offshore LNGC size:130,000–220,000 m^3 Maximum unloading rate = 10,000 m^3/h	Onshore LNGC size:5000–260,000 m^3 Maximum unloading rate = 14,000 m^3/h
3	Storage	2 units 130,000 m^3 (FSRU)	2 units 200,000 m^3 full containment and LNG tank
4	Vaporization Scheme	IFV with propane as an intermediate fluid and the heating medium is seawater	ORV with sea water as the heating medium
5	Capacity	3.8 MTPA (500 mmscfd)	3.5 MTPA (490 mmscfd)

2. Cold Energy Utilization and Regasification System

2.1. Cold Energy Utilization

He et al. [8] published a review on the current and future utilization of cold energy. A summary of the review is provided in Table 2. In the context of this study, the focus is on the application of waste cold energy for air-conditioning. Waste cold energy from regasification can be captured and stored by using a thermal energy storage (TES) system with chilled water as a cooling medium. The chilled water is used for air conditioning.

Table 2. Current and future utilization of cold energy [8].

	System	Specific Technology	Function of LNG Cold Energy
Current	Cryogenic Power Generation	Organic Rankine Cycle	As heat sink of the cycle
		Brayton Cycle	Reduce the inlet gas temperature
		Kalina Cycle	As heat sink of the cycle
		Combined with gas turbine cycle	Inlet air cooling and intercooling
	Air Separation		Cool the air temperature and replace the external refrigeration cycle
	Seawater Desalination		Cool the seawater
	Cryogenic Carbon Dioxide Capture		Cool and liquefy carbon dioxide

Table 2. *Cont.*

	System	Concepts
Potential	Data Center Cooling	Using LNG cold energy as the source to produce the cooling medium for data center cooling which can reduce energy consumption and greenhouse emissions.
	Clathrate Hydrate-based Desalination	Using LNG cold energy to cool the seawater, hydrate the former, and remove the reaction heat of the clathrate hydrate-based desalination
	Cold Chain for Food Transportation	Using LNG cold energy as the cooling source of the cold warehouse and trucks for storage and ease of transportation
	Cold Energy Storage	Transferring LNG cold energy into an appropriate energy form for longer storage and to ease of transportation
	Utilization of FSRU	Recover LNG cold energy on FSRU by power generation or utilize it for FSRU

2.2. Regasification System

Figure 1 shows the overall process of regasification at RGTSU and RGTPJ.

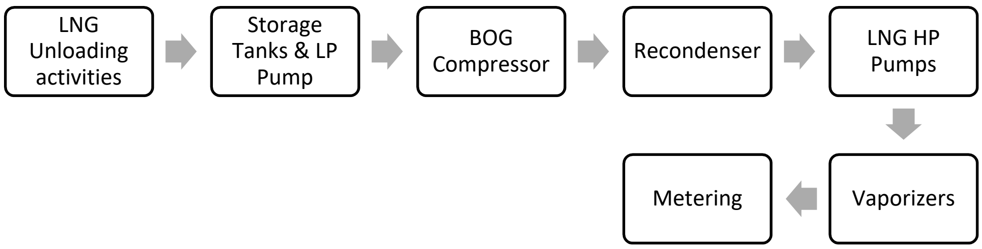

Figure 1. Regasification processes at Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

During the regasification process, the cold energy of LNG, which is approximately 830 kJ/kg, is released into seawater by LNG vaporizers.

Several vaporization schemes are utilized in regasification technology, including submerged combustion vaporizers (SCRs), ORV, IFV, and super ORVs. A literature survey found that 70% of the regasification terminals used ORV and another 25% and 5% used SCR and IFV, respectively [9,10]. The RGTSU uses IFV (Figure 2). This system consists of two heat exchangers operating in series using propane for intermediate heat transfer (HTF). Propane is used intentionally to prevent the seawater from freezing. The vaporizer is arranged in series to allow the first evaporator exchanger to use the latent heat of propane condensate to partially heat the LNG, and a second heat exchanger uses seawater to further heat the LNG to the required final temperature.

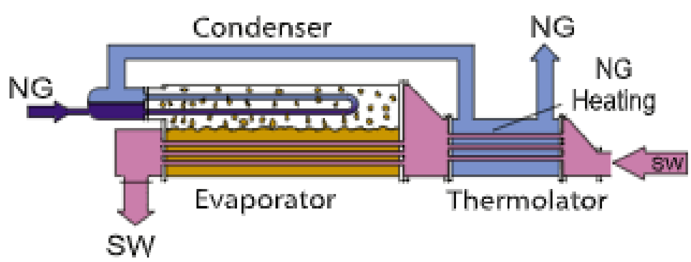

Figure 2. Intermediate-Fluid-Vaporization [11].

The RGTPJ uses ORV (Figure 3). This process employs ribbed-shaped tubes as heat exchangers and seawater as a heat source [11]. The process uses heat transfer between seawater and LNG. Seawater ranging in temperature from 5 to 15 °C is used to heat the LNG from −162 or −163 °C to obtain NG at atmospheric temperature. Seawater temperatures below approximately 5 °C are usually not practical because of seawater freezing [12]. ORV is a well-proven technology and has been widely used in Korea, Europe, and Japanese LNG terminals [10]. Figure 3 shows a schematic diagram of the ORV system.

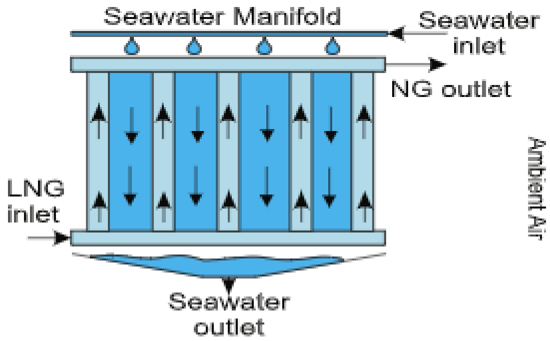

Figure 3. Open-Rack Vaporization [11].

A literature review found that many previous studies exist on LNG cold energy [13–19]. García et al. [20] reported that the regasification of LNG is the last step in the LNG supply chain carried out at LNG terminal storage plants [20]. LNG regasification cold energy can be extensively manipulated into useful energy, which can be applied to cold power generation, seawater desalination, polygeneration, cold air separation, cryogenic crushing, frozen food storage, and carbonic acid production [21]. Such applications can prevent vast stores of cold energy from being thrown away during regasification.

The method for recovering the energy stored in LNG to produce power can be classified into mechanical energy recovery and thermal energy recovery [22]. Mechanical energy recovery uses turbines with LNG as a working fluid [23,24]. Thermal energy recovery uses cycles, such as Rankine, Brayton, and Kalina, and combined forms of these cycles [18,19,25–29]. Despite efforts to utilize this cold energy, approximately 80% of the cold energy from LNG imported globally is still being wasted [30]. The current practice in Malaysia is for cold energy to be released from RGTPJ and RGTSU into the environment via seawater. It is not utilized for any process, whether through mechanical or thermal energy recovery.

Several review papers focused on utilizing LNG cold energy. These reviews mainly focused on progress in power generation utilization without addressing potential applications in which an emerging country, such as Malaysia, can venture. By definition, LNG cold energy utilization systems refer to those requiring low-temperature operating conditions that can be integrated into the LNG regasification process without drastically modifying the system. The potential applications for which cold energy can be utilized without drastically modifying the system include NGL recovery, data center cooling, clathrate hydrate-based desalination, cold chains for food transportation, cold energy storage, and a floating storage regasification unit.

RGTPJ is a land-based regasification terminal that allows for better potential utilization of cold energy for NGL recovery, data center cooling, cold chains for food transportation, and cold energy storage. Meanwhile, RGTSU is best for FSRUs and clathrate hydrate-based desalination given its location offshore. Because of the potential discoveries of these applications, data were gathered from RGTSU and RGTPJ to determine how much cold waste energy can be recovered or potentially utilized through an energy analysis. This study evaluated the potential of using the available cold energy for space cooling by using a TES system.

3. Materials and Method

To evaluate the cold energy available from regasification, temperature, pressure, and flow rate data were acquired for further analysis. These data were acquired at vaporizers and pumps to determine the net energy generated during evaporation. Figure 4 shows the process flow for vaporizers and pumps at RGTSU and Figure 5 shows schematic diagrams of the vaporizers and pumps at RGTPJ. In both flow schemes, LNG from storage at near-atmospheric pressure is sent out through a high-pressure liquid pump to vaporizers. The boiled-off gas from storage is compressed and recondensed before being pumped to the vaporizers.

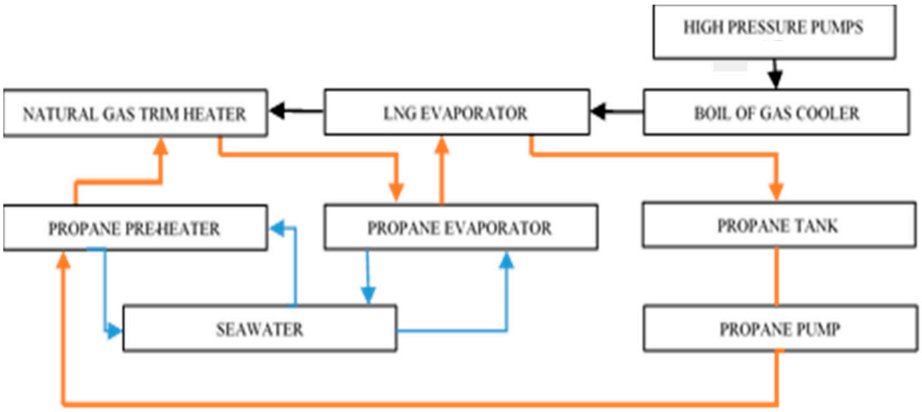

Figure 4. Setup for vaporizers or evaporators and pumps at Regasification Terminal Sungai Udang [31].

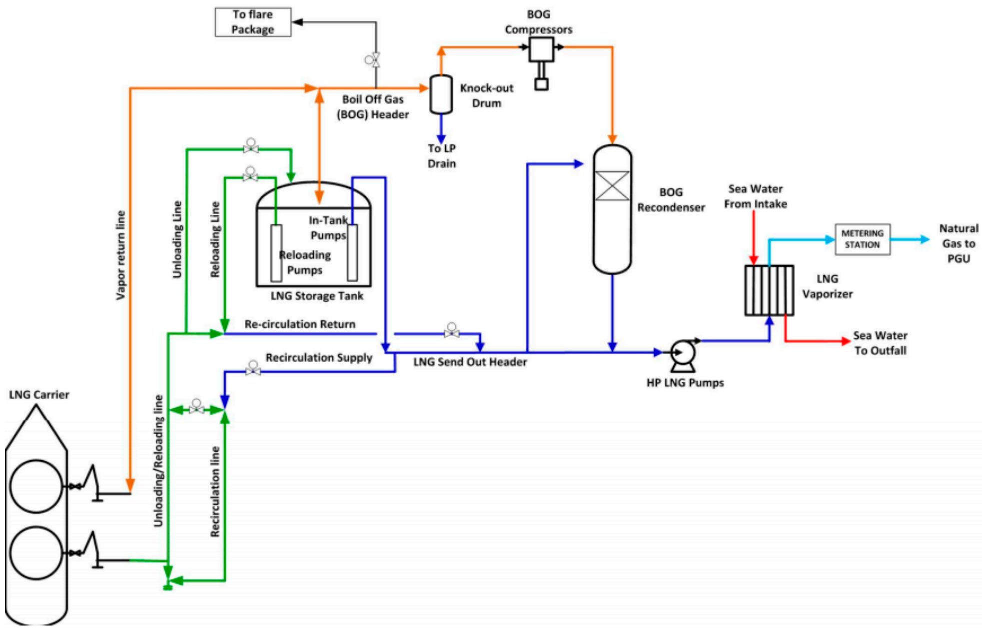

Figure 5. Setup for vaporizers or evaporators and pumps at Regasification Terminal Pengerang Johor [32].

3.1. Energy Models for RGTPJ and RGTSU

RGTPJ and RGTSU regasification processes were simplified as a block diagram, as shown in Figure 6. LNG at −162 °C is heated to normal operating NG between 12 and 20 °C using seawater. With reference to the first law of thermodynamics, the energy balances of the evaporators of RGTPJ and RGTSU were modeled as free-body diagrams, as illustrated in Figure 7. Cold energy generated during the vaporization process of converting LNG to NG is transformed into heat and work energy through the vaporizers.

For this ideal process, the energy available is freely released into the environment. The amount of energy released is estimated using the first law of thermodynamics as per Equation (1):

$$Q = \dot{m}_{sw}\ Cp_{sw}\ (T_{swout} - T_{swin}), \tag{1}$$

where Q, $\dot{m}_{sw}$, Cp_{sw}, T_{swout}, and T_{swin} are the total heat energy (kW), mass flow rate (kg/s), specific heat capacity (kJ/kg °K), and inlet and outlet temperatures (°C) of seawater, respectively.

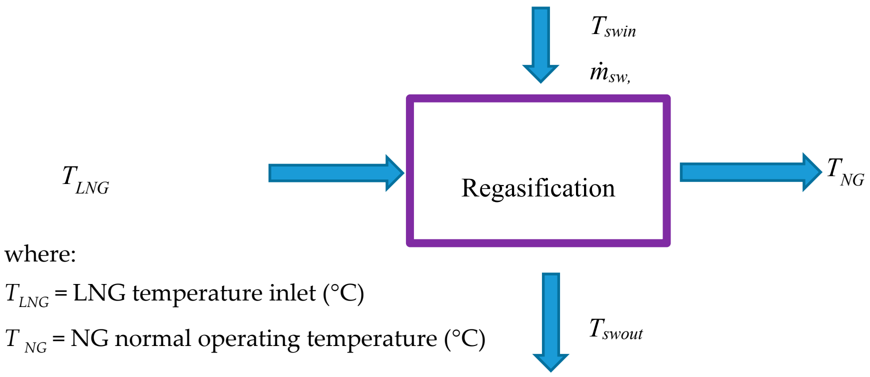

Figure 6. Simplified free-body diagram of the regasification process Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

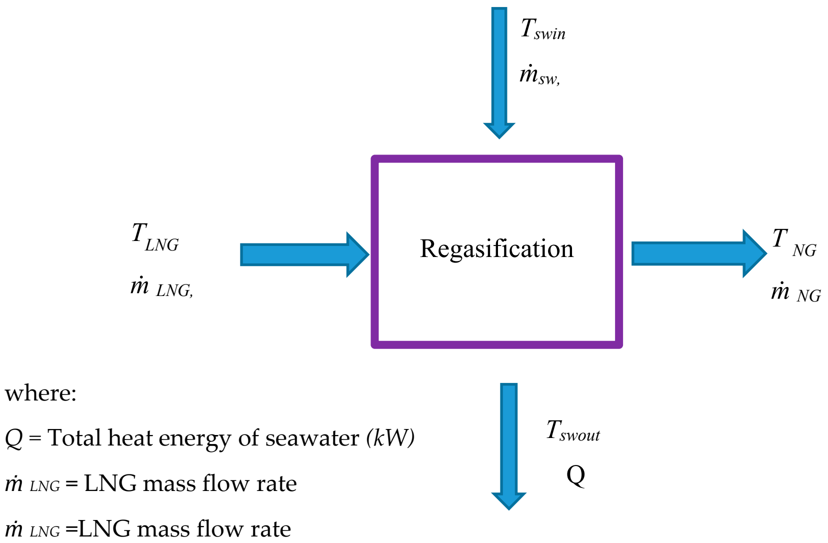

Figure 7. Energy balanced model of regasification Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

3.2. Economic Models for RGTPJ and RGTSU

To evaluate the economic value of the available cold energy from LNG regasification, an economic analysis was performed. For the analysis, it was assumed that the available waste cold energy is to be converted to the cooling energy of chilled water (CW) at 70% thermal efficiency. A CW system was adopted as the thermal energy storage system (TES) and the CW was used for space cooling. An internal rate of return (IRR) based on the present worth (PW) was adopted for the analysis. IRR was evaluated for a project life from year 1 to year 20 for both RGTPJ and RGTSU. Since the values of the parameters used for evaluating the IRR were based on estimates, sensitivity analyses for IRR were evaluated for years 5, 10, 15, and 20, respectively. Life cycle costing (LCC) for project life of 5, 10, 15, and 20 years were also evaluated for both projects. The steps adopted for the economic analysis are as shown in Figure 8.

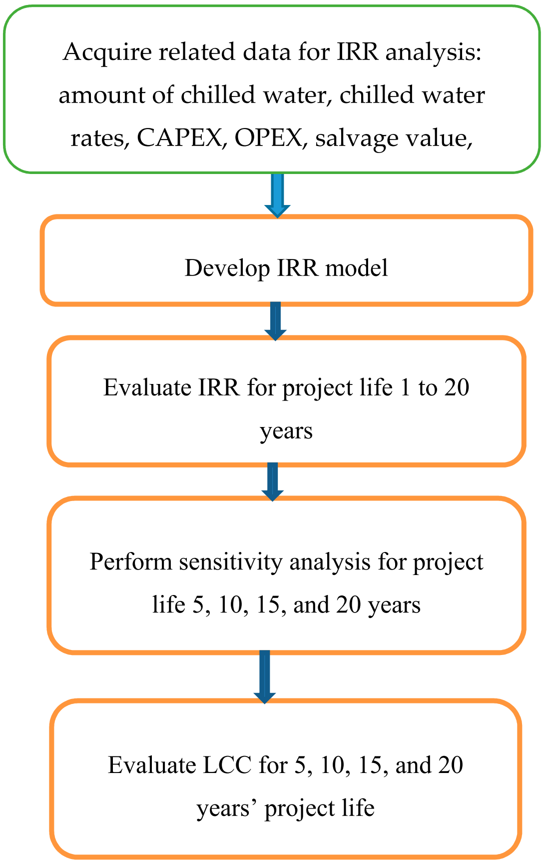

Figure 8. Methodology for the economic analysis for Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

The steps adopted for the economic analysis were:

i Identified data required for the analysis. The data included the amount of CW that could be generated from LNG regasification, estimated capital expenses (CAPEXs), operating expenses (OPEXs), salvage value (Sal) of the equipment at the end of the project's life, and the CW rate. The estimated data for both RGTPJ and RGTSU are included in Table 2.

ii Developed the IRR models for both RGTSU and RGTPJ. The principle used to develop the IRR models was a present worth (PW) analysis of the revenue and the PW of expenses. The PW revenue was taken as being equal to the net annual revenue (NAR), which was equal to the revenue generated from CW minus OPEX as per Equation (2):

$$\text{PW of NAR} + \text{PW of salvage value} = \text{CAPEX}, \tag{2}$$

$$\text{PW NAR} = \text{NAR}\ (P/A, \text{IRR}, N) \tag{3}$$

where:

NAR (nett revenue) = annual revenue − annual OPEX;
NAR (P/A, IRR, N) = PW component for the net revenue;
Sal = salvage value;
Sal (P/F, IRR, N) = PW component for the salvage value;
CAPEX = investment cost;
(P/A, IRR, N) = uniform series PW at discount rate IRR and year N of project life; and
(P/F, IRR, N) = single payment PW at discount rate IRR and year N of project life.

iii The IRR for RGTPJ and RGTSU were evaluated for project life year 1 up to year 20.

iv Sensitivity analysis for both RGTPJ and RGTSU was done for the case of project life years 5, 10, 15, and 20 based on the evaluated IRR. Equations (4) and (5) were used for the sensitivity analysis [33]:

$$\text{PW(IRR)} = 0 = \text{-CAPEX}(1 + x) + \text{NAR (P/A, IRR,5)} + 0.02 \times \text{CAPEX (P/F, IRR, N)}, \quad N = 5, 10, 15, \text{and } 20, \tag{4}$$

$$\text{PW(IRR)} = 0 == \text{-CAPEX} + (\text{NAR } (1 + y))\ \text{(P/A, IRR, N)} + 0.02 \times \text{CAPEX (P/F, IRR, N)}, \quad N = 5, 10, 15, \text{and } 20, \tag{5}$$

where:

For CAPEX, x = percent change in CAPEX; and

For NAR, y= percent change in NAR.

v Evaluate LCC for the project life of 5, 10, 15, and 20 years.

The LCC models were based on the PW formula for 5, 10, 15, and 20 years. The general LCC model was based on Equation (6).

The LCC models consist of three main components of CAPEX, NAR, and salvage values. The NAR and salvage values were discounted to the current year using the PW formula. The main items that influence the LCC are CAPEX, amount of chilled water, and project life. Hence, if the CAPEX, amount of chilled water and project life change, the IRR will also change, leading to changes in the NAR and salvage value components, and hence, the LCC model:

$$LCC_N = \text{-CAPEX} + [\text{RT} \times 24 \times 300 \times 0.549 \times 0.8(\text{P/A}, IRR_N, N)/1{,}000{,}000 - 0.3 \times \text{CAPEX}] + 0.02 \times \text{CAPEX (P/F}, IRR_N, N), \tag{6}$$

where the term + [RT × 24 × 300 × 0.549 × 0.8 (P/A, IRR_N, N)]/1,000,000 – 0.3 × CAPEX + 0.02 × CAPEX (P/F, IRR_N, N) represents the PW of NAR in RM million discounted to the current with the IRR for the specific N, while the terms RT × 24 × 300 × 0.549 × 0.8(P/A, IRR_N, N), 0.3 × CAPEX, and 0.02 × CAPEX (P/F, IRR_N, N) represent the revenue in million RM, annual operating expenses, and the PW of salvage value at the end of year N, respectively.

4. Results and Discussion

4.1. Energy Availability and IRR for the Project Life from Years 1 to 20

The amount of energy availability was calculated using Equation (1) and the following assumptions:

- No losses on the flow rate of seawater from the evaporation process; and
- The amount of Q from seawater is 100% converted into energy availability.

Table 3 shows the estimated daily amount of waste cold energy that was available during regasification processes at RGTPJ and RGTSU, respectively. The estimated available waste cold energy daily during regasification are 47,214 and 88,383 kWh at RGTPJ and RGTSU, respectively. In terms of RTh equivalent, the daily amount was 9398 and 17,592 RTh for RGTPJ and RGTSU, respectively. This was based on an assumption of 70% thermal efficiency for the conversion of waste cold energy to chilled water. Using the economic data from Table 4, at 7200 h per year operation, 80% availability, and 0.549RM per RTh, IRR for the project life from year 1 to year 20 were evaluated for RGTPJ and RGTSU. The evaluated IRR for RGTPJ varies from –65% to 33% while for RGTSU, the IRR varies from –80% to 17%. The negative IRR values are IRR during the early years of project life. A Plot of IRR vs. years for both RGTPJ and RGTSU is shown in Figure 9. Results from the IRR analysis indicate that the project could be a profitable venture. RGTPJ gives higher returns compared to RGTSU; the lower returns for RGTSU are due to the higher CAPEX requirements for RGTSU.

Table 3. Energy availability at RGTPJ and RGTSU.

	Seawater Inlet	Seawater Outlet	Energy Availability (kW per hour)	RT/hr (70% Thermal Efficiency Conversion of Energy to CW)
RGTPJ	m_{fsw} = 5800 m^3/h T_{swin} = 30 °C	m_{fsw} = 5800 m^3/h T_{swo} = 23 °C	47,214	9398
RGTSU	m_{fsw} = 7600 m^3/h T_{swin} = 30 °C	m_{fsw} = 7600 m^3/h T_{swo} = 20 °C	88,383	17,592

Table 4. Economic analysis assumptions and data for RGTPJ and RGTSU.

	TES Tank Capacity and Auxiliary	Major Equipment Cost/CAPEX (RM)	Annual Expenses (OPEX), RM	Estimated Production Rate and Cost
RGTPJ	• 2 Units: TES Tank @ capacity 10,000 RTh • 2 Units: Heat exchanger @ 250 RT/unit • High pressure pump • Miscellaneous	39.9 M	12.0 M	• CW quantity @ 9398 RT/h • Working hours @ 7200 h/year • CW rates @ RM 0.549/RTh • Availability factor @ 0.8
RGTSU	• 3 Units: TES Tank @ capacity 10,000 RTh • 4 UnitsPlate heat exchanger @ 250 RT/unit • 4 units: High pressure pumps • Miscellaneous	89.34 M	26.8 M	• CW quantity @ 17,592 RT/h • Working hours @ 7200 h/year • CW rates @ RM 0.549/RTh • Availability factor @ 0.8

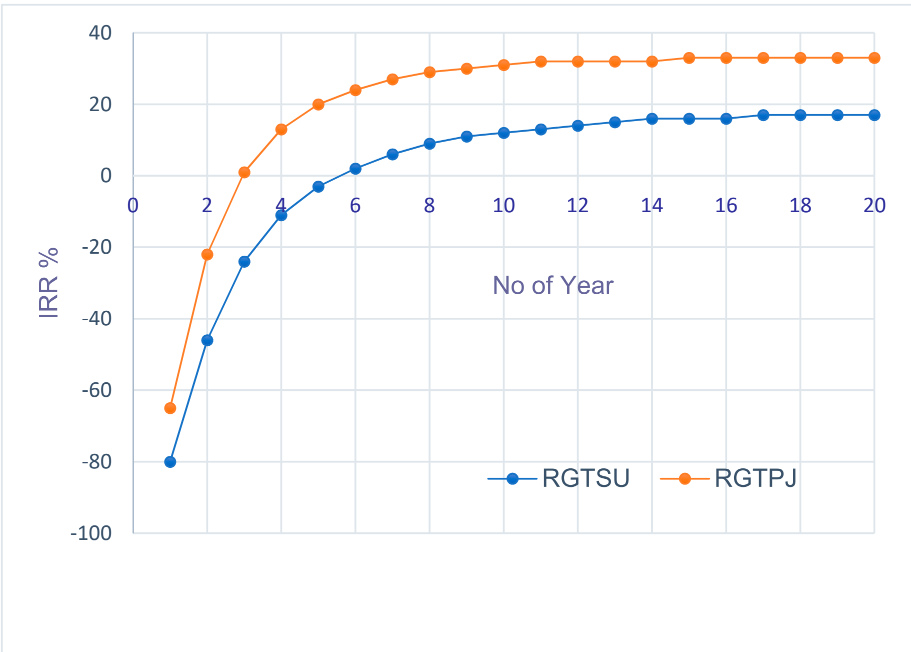

Figure 9. Internal rate of return vs. year for Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

4.2. Sensitivity Analysis

Since all costs were based on estimates, it is possible that the estimates might not be accurate. It is then essential to evaluate the breakeven points for both CAPEX and NAR. These values were evaluated using Equations (4) and (5), adjusted for RGTSU and RGTPJ as follows:

For RGTSU:

The adjusted sensitivity equation for CAPEX:

$$PW(IRR) = 0 = -89.34(1 + x) + (\text{Annual Revenue - OPEX})_N\ (P/A, IRR, N) + 0.02(89.34)(P/F, IRR, N), N = 5, 10, 15 \text{ and } 20. \quad (7)$$

The adjusted sensitivity equation for net annual revenue (NAR):

$$PW(IRR) = 0 = -89.34 + (\text{Annual revenue - OPEX})_N\ (1 + y))\ (P/A, IRR, N) + 0.02 \times 89.34(P/F, IRR, N), N = 5, 10, 15 \text{ and } 20. \quad (8)$$

For RTJPJ:

The adjusted sensitivity equation for CAPEX:

$$PW(IRR) = 0 = -39.9(1 + x) + (\text{Annual Revenue - OPEX})_N\ (P/A, IRR,N) + 0.02(39.9)(P/F, IRR, N), N = 5, 10, 15 \text{ and } 20. \quad (9)$$

The adjusted sensitivity equation for net annual revenue (NAR):

$$PW(IRR) = 0 = -39.9 + (\text{Annual revenue - OPEX})_N\ (1 + y)(P/A, IRR, N) + 0.02 \times 39.9(P/F, IRR, N), N = 5, 10, 15 \text{ and } 20. \quad (10)$$

Using Equations (7)–(10) and taking the forecasted annual revenue, OPEX, and the evaluated IRR for the respective project life of 5, 10, 15, and 20 years, the values of x and y were calculated for both RGTPJ and RGTSU, respectively. The evaluated results are included in Table 5.

Table 5. Sensitivity of Internal rate of return for Capital expenditure and Nett annual revenue

RGTPJ	IRR	x (CAPEX)	y (Nett Revenue)	Remarks
5	20	0.34	−1.75	If CAPEX increases by more than 0.34% project not viable If NAR is lower by more than 1.75% project not viable
10	31	0.34	−1.75	If CAPEX increases by more than 0.34% project not viable If NAR is lower by more than 1.75% project not viable
15	33	0.33	−1.75	If CAPEX increases by more than 0.34% project not viable If NAR is lower by more than 1.75% project not viable
20	33	0.34	−1.74	If CAPEX increases by more than 0.34% project not viable If NAR is lower by more than 1.74% project not viable
RGTSU	**IRR %**	**x**	**y**	**Remarks**
5	−3	NA	−NA	NA due to negative IRR
10	12	0.83	−1.54	If CAPEX increases by more than 0.83% project not viableIf NAR is lower by more than 1.54% project not viable
15	16	0.8	−1.55	If CAPEX increases by more than 0.8% project not viableIf NAR is lower by more than 1.55% project not viable
20	17	0.82	−1.55	If CAPEX increases by more than 0.82% project not viableIf NAR is lower by more than 1.55% project not viable

For RGTPJ, the sensitivities for CAPEX are 0.34%, 0.34%, 0.34%, and 0.34% for years 5, 10, 15, and 20, respectively. For NAR, the sensitivities are −1.7%5, −1.75%, −1.75%, and −1.74% for years 5, 10, 15, and 20, respectively.

For RGTSU, the CAPEX sensitivities are NA, 0.83%, 0.8%, and 0.82% for years 5, 10, 15, and 20, respectively. While for NAR, sensitivities are NA, −1.54%, −1.55%, and −1.55% for years 5, 10, 15, and 20, respectively.

4.3. LCC Models

Using Equation (6), the LCC models for RGTPJ and RGTSU were formulated. The LCC models are included in Table 6.

Table 6. Life cycle cost models for Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor for year 5, 10, 15, and 20.

Project Life	**RGTPJ** $\mathbf{LCC_N = -CAPEX + [RT \times 24 \times 300 \times 0.549 \times 0.8(P/A, IRR_N, N)/1{,}000{,}000 - 0.3 \times CAPEX] + 0.02 \times CAPEX(P/F, IRR_N, N)}$
5	$LCC_5 = -39.9 + [9398 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 20,5)/1{,}000000 - 0.3 \times 39.9] + 0.02 \times 39.9(P/F, 20,5)$
10	$LCC_{10} = -39.9 + [9398 \times 24 \times 300 \times 0.549 \times 0.8(P/A,31,10)/1{,}000{,}000 - 0.3 \times 39.9] + 0.02 \times 39.9(P/F, 31,10)$
15	$LCC_{15} = -39.39 + [9398 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 33,15)/1{,}000{,}000 - 0.3 \times 39.9] + 0.02 \times 39.9(P/F, 33,15)$
20	$LCC_{20} = -39.9 + [9398 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 33,20)/1{,}000{,}000 - 0.3 \times 39.9] + 0.02 \times 39.9(P/F, 33,20)$
	RGTSU $LCC_N = -CAPEX + [RT \times 24 \times 300 \times 0.549 \times 0.8(P/A, IRR_N, N)/1{,}000{,}000 - 0.3 \times CAPEX] + 0.02 \times CAPEX\ (P/F, IRR_N, N)$
5	$LCC_5 = -89.34 + [17592 \times 24 \times 300 \times 0.549 \times 0.8(P/A, -3,5)/1{,}000{,}000 - 0.3 \times 89.34] + 0.02 \times 89.34(P/F, -3,5)$
10	$LCC_{10} = -89.34 + [17592 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 12,10)/1{,}000{,}000 - 0.3 \times 89.34] + 0.02 \times 89.34(P/F,12,10)$
15	$LCC_{15} = -89.34 + [17592 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 16,15)/1{,}000{,}000 - 0.3 \times 89.34] + 0.02 \times 89.34(P/F, 16,15)$
20	$LCC_{20} = -89.34 + [17592 \times 24 \times 300 \times 0.549 \times 0.8(P/A, 17,20)/1{,}000{,}000 - 0.3 \times 89.34] + 0.02 \times 89.34(P/F, 17,20)$

It is noted that the CAPEX, the present worth components for the revenue from chilled water, operating cost, and to lesser extent, the salvage value influence the LCC.

Using the equations in Table 6, LCC for RGTSU and RGTPJ were evaluated. Results for both RGTSU and RGTPJ are tabulated in Table 7.

Table 7. Evaluated Life cycle cost for Regasification Terminal Sungai Udang and Regasification Terminal Pengerang Johor.

	RGTSU	
Project Life	**IRR**	**LCC Value (million RM)**
5	−3	NA due to negative IRR
10	12	198.74
15	16	194.22
20	17	197.01
	RGGPJ	
Project Life	**IRR**	**LCC Value (million RM)**
5	20	37.33
10	31	39.61
15	33	36.95
20	33	37.88

The LCC results for RGTSU vary from 197 to RM198.7 which are of higher values compared to RGTPJ LCC values, which vary from RM37.3 million to RM39.6 million. This is due to higher CAPEX value for RGTSU compared to RGTPJ.

5. Conclusions

Currently, the two regasification terminals operated by PETRONAS Gas Sdn Bhd do not capture waste cold energy during the regasification process. This study noted that substantial waste cold energy is available during regasification at both RGTPJ and RGTSU. The estimated annual amount of cold energy that could be captured daily during regasification at RGTPJ and RGTSU is 47,214 and 88,383 kWh, respectively. The study evaluated the commercial potential of using the available cold energy for chilled water generation. The chilled water is to be used for space cooling. Assuming 70% thermal efficiency conversion of waste cold energy to chilled water, it was estimated that daily, the amount of cold energy available hourly during regasification at RGTPJ and RGTSU is equivalent to 9398 and 17,592 RTh amount of chilled water, respectively. From the economic feasibility study, commercially, the revenue from the chilled water could give IRR greater than 20% for RGTPJ for a project life of 5 to 20 years. For RGTSU, the IRR values are 12% to 17% for a project life of 10 to 20 years. Hence, if the waste cold energy during regasification at RGTPJ and RGTSU is exploited, it would give a profitable venture. In addition, the venture would also increase the efficiency of LNG regasification at both terminals and the economic benefit of the LNG supply chain. Besides using the cold energy for generating CW, the waste cold energy could also be used to cool intake air for the gas turbines. Since RGTPJ is located near the vicinity of a cogeneration plant, the cold energy from regasification should also be considered for use for cooling intake air for the gas turbines at the cogeneration plant. It is therefore recommended that the owners of RGTPJ and RGTSU should consider installing systems able to capture the waste cold energy during regasification of LNG at both terminals.

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Nomenclature

RGTSU	Regasification terminal Sungai Udang Melaka
RGTPJ	Regasification terminal Pengerang Johor
LNG	Liquified natural gas
LNGC	LNG Carrier
NG	Natural gas
CW	Chilled water
Q	Total waste cold energy
$\dot{m}_{sw}$	Seawater mass flow rate
Cp_{sw}	Seawater specific heat capacity
T_{swout}	Seawater temperature outlet
T_{swin}	Seawater temperature inlet
RTh	Refrigeration ton hour
TES	Thermal energy storage
CAPEX	Capital cost
OPEX	Operation expenses
NAR	Nett annual revenue
PW	Present worth
Sal	Salvage value
IRR	Internal rate of return
LCC	Life cycle costing

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