Semnan University

Journal of Modeling in Engineering

Journal homepage: https://modelling.semnan.ac.ir/

ISSN: 2409-2728

Techno-Economic Modeling of the High-Efficient Self-Cooling Natural Gas Liquefaction System in Pressure Reduction Stations: a Case Study of Shahid Salimi Power Plant of Neka

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Received: 2024-09-15 Revised: 2025-08-02 Accepted: 2025-08-18

Abstract

Today, the demand for natural gas (NG) as a low-emission energy carrier is on the rise. Simultaneously, the share of liquefied natural gas (LNG) as a method of gas transportation is also increasing. The high-pressure gas pipelines for urban gas supply, along with pressure reduction stations (PRSs), have expanded significantly in Iran over the past few years. In the PRS, the pressure energy of NG is lost. Therefore, LNG production using the self-cooling method in PRS (LPRS) is one solution to recover this energy and produce LNG simultaneously. This method requires attention due to very low electricity consumption and simplicity compared to other liquefaction methods. Replacing LPRS instead of PRS, in addition to creating a product sales market, can decrease energy waste in PRS. The feasibility of the plant construction requires both technical and economic evaluations. In this research, we have designed an LPRS process specifically for the Neka power plant. After identifying suitable thermodynamic points, an economic evaluation that considered the entire LNG production chain is conducted. The proposed process achieved a liquefaction rate of 27.6%, accompanied by low specific power consumption and favorable exergy efficiency. Moreover, the economic analysis demonstrated the promising economic viability of the proposed process.

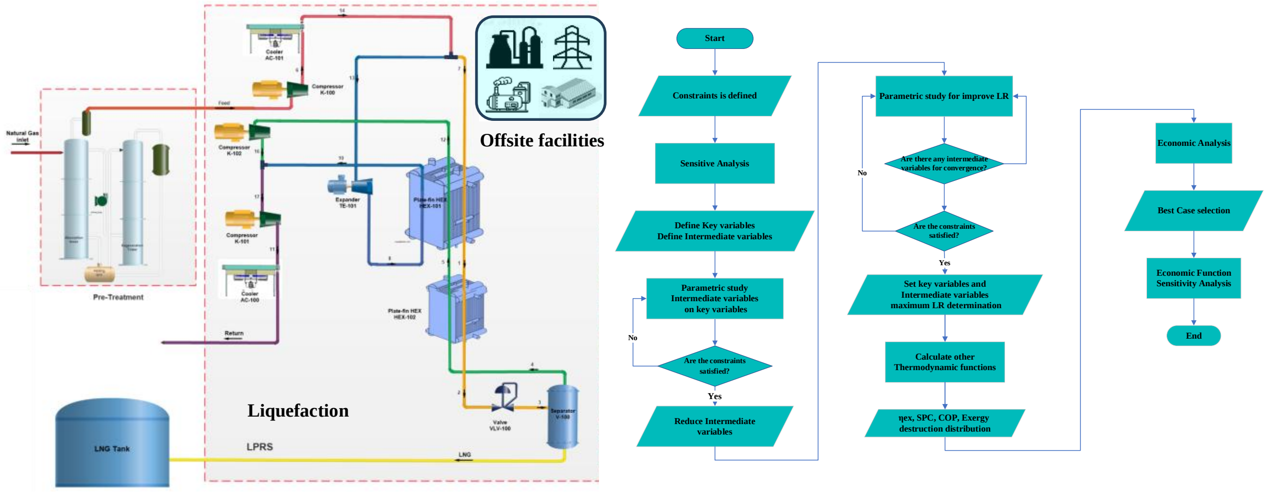
Keywords:
Liquified Natural Gas (LNG), Pressure reduction station (PRS), Expander, Parametric study, Liquefaction rate (LR), internal rate of return (IRR), break-even point (BEP).

1. Introduction

Energy demand rises with population growth [1]. Natural gas (NG) is gaining share as a low-carbon, high-heating-value fuel [2], and LNG trade has more than tripled since 2000 and is projected to overtake pipelines by 2035 [3]. Liquefaction plants are classified by capacity into baseload, small-scale, and offshore units [4]; small-scale technologies include the closed nitrogen cycle, the mixed refrigerant cycle, and NG self-refrigeration [5], the first two being more widely investigated, whereas self-refrigeration suits high-pressure feeds. In Iran, high-pressure pipelines have been developed nationwide, and the gas pressure is reduced at pressure reduction stations (PRSs). In a conventional PRS, the throttling valve and the gas heating requirement waste energy. Replacing the PRS with a self-refrigeration liquefaction process (LPRS) recovers this energy, with low power consumption and capital cost [6]. The main challenge is the low liquefaction rate (LR): early designs with a throttling valve achieved only 2–4% [7]. He and Ju [8] reached 13% with a dual-turboexpander process, optimized by Tan et al. [9] to 17.8%; Li et al. [6] reported a maximum of 23.1%. However, an LR above 20% has been achieved only at feed pressures above 60 bar; in the present case, it is 45 bar. In this study, a self-refrigeration liquefaction process is designed to recover the wasted energy of the Neka power plant PRS. The LR is improved through a parametric study, other performance functions and economic indicators—CAPEX, IRR, and the break-even point (BEP)—are evaluated, and a sensitivity analysis is conducted.

2. Methodology

A self-refrigeration LNG production process without a closed refrigeration cycle was synthesized, in which a portion of the feed is liquefied by the turboexpander cooling duty, yielding a low-pressure product (1.2 bar) suitable for storage in flat-bottom LNG tanks. The economic analysis considers a complete plant—pre-treatment, LPRS, storage, and offsite facilities (Fig. 1a).



a b

Figure 1. (a) Schematic of the proposed LPRS plant, including pre-treatment, liquefaction, storage, and offsite facilities; (b) Flowchart of the stepwise algorithm for design-point selection.

The feed is liquefied in plate-fin heat exchangers and, after the throttling valve, is separated into LNG and off-gas. A side stream provides the cooling duty in the turboexpander, and the return gas is pressurized to 4.5 bar at 40 °. Fluid properties were calculated with the Peng–Robinson equation of state [10] together with the mass and energy conservation laws under steady-state conditions. The assumptions include negligible heat-exchanger pressure drop, compressor and turboexpander isentropic efficiencies of 75% and 85%, a turboexpander outlet vapor quality above 99%, full transfer of the turbine work to the compressor, a minimum approach temperature of 3 K, and a feed flow rate of 20 tons/h. Four performance indicators are defined: the liquefaction rate (LR), the ratio of the LNG mass flow rate to the feed, the most important indicator of self-refrigeration processes; the specific power consumption (SPC), the net power per unit mass of LNG; the equivalent coefficient of performance (COP_{eq}), the ratio of the refrigeration capacity to the equivalent consumed work (pressure energy plus compressor power); and the exergy efficiency, the ratio of the product exergy (LNG and power) to the consumed exergy, including the stream exergy differences, consumed power, and cooler exergy destruction. The cost estimation is based on the Guthrie method [11]; the equipment prices were estimated [12-14] and converted into the total bare module cost (C_{TBM}) [11] for the target year of 2023. The CAPEX comprises the LPRS, buildings, site preparation, off-site facilities, pre-treatment, and storage units. The operating expenditure (OPEX) includes natural gas (14 ¢/m³), electricity (8 ¢/kWh), and maintenance (4% of the total capital investment (TCI) in the first year, 5% annual growth, 20-year lifetime). An algorithm based on the step-by-step reduction of the degrees of freedom was developed to select the appropriate design point (Fig. 1b), avoiding the computational cost of complex optimization while providing insight into the system behavior. First, the problem constraints are defined. Then, a sensitivity analysis of the LR identifies the key variables, and the effect of the intermediate variables on them is evaluated to fix the less influential ones. Subsequently, the LR is maximized through a parametric study; the feed compressor discharge pressure (P_6) is treated as an external variable, and the performance trends are examined over its variations. Finally, at the maximum-LR points, the remaining thermodynamic functions and the economic indicators are calculated, the economically optimal P_6 is selected, and a sensitivity analysis on variables such as the product price is performed.

3. Discussion and Results

The evaluation begins with defining the constraints; the first step is a sensitivity analysis of the variables on the LR. The results show that MFR and T_1 are the main determinants of the LR, whereas P_8 affects the convergence of the solution and functions such as the SPC. As shown in Fig. 2 for $P_6 = 50$ bar, at a constant T_1 the LR increases with MFR up to the unfeasible area, where the maximum LR is achievable. The function is concave downward.

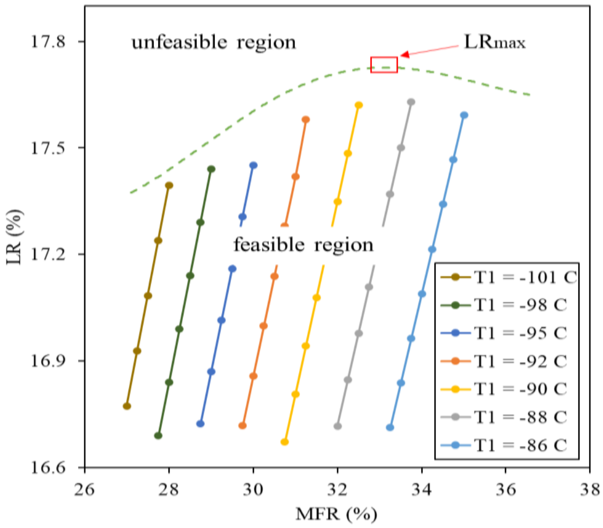


Figure 2. Variations of the LR with MFR at different T_1 values (P_6 = 50 bar).

When the thermodynamic conditions for the maximum LR determined, the other performance functions were calculated at the maximum-LR points for each P_6. The LR is directly related to P_6 : increasing P_6 raises the turboexpander pressure ratio, lowers the main heat exchanger outlet temperature (T_1), and—through the higher refrigeration capacity—allows the main stream flow rate (MFR) to increase; hence both key variables improve. In contrast, the exergy efficiency decreases consistently with P_6 despite growing product and consumed exergy; the SPC increases steeply. Taking the LR as the criterion function, P_6 = 90 bar is the best thermodynamic point. As Table 1 shows, the present process achieves a higher LR than the other studies with acceptable exergy efficiency and power consumption, particularly at the low feed pressure of 45 bar.

Table 1. Comparison of the present process with previous studies (thermodynamic performance)

		P_{feed}	LR	η_{ex}	SPC	Ref.
		bar	%	%	kWh/ton LNG	
This study	-	**45**	**27.6**	**61.8**	**160.0**	
Li	I	100	20.92	30.9	314.0	[6]
	II	100	23.13	54.5	103.0	
Guo		31	36.21	34.4	391.2	[14]
Tan		40	17.8	NA	0.0	[9]

The assumptions for the economic calculations are given in Table 2. The result shows that Without the feed compressor, CAPEX, OPEX, and revenue are lowest, at 23, 6, and 13 million USD, respectively; with the compressor and increasing P_6, all three rise monotonically.

Table 2. Economic assumptions of the case study

PAREMETER	UNIT	COUNT	PAREMETER	UNIT	COUNT
Feed flow rate	kg/h	20,000	Construction time	Year	3
Annual operation period	day	330	Plant life cycle	Year	20
Storage time capacity	day	30	Discount rate	%	10
LNG price	$/tons	658	Operation cost ratio from CAPEX	%	4.0
Natural Gas price	$/tons	200	Operation increase rate	%	5.0
Electricity price	₵/kWh	8.06			

As shown in Fig. 3, the BEP falls to 2.4 years at 90 bar while the IRR rises to its maximum of 38%; hence, 90 bar offers the best economic performance. The calculations involve uncertainties—a possible product price decline, equipment cost estimation errors, and reduced plant operating days due to gas supply limitations in cold seasons. The results show that a lower LNG price, a shorter operating life, and higher equipment costs significantly affect the IRR and BEP.

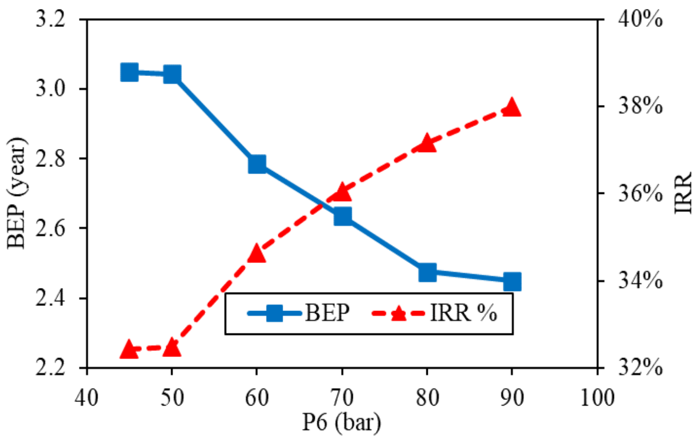


Fig. 3. Variations of the BEP and IRR with the feed compressor discharge pressure (P_6).

4. Conclusions

A self-refrigeration LNG production process was designed by recovering the pressure energy at the Neka power plant PRS. The main findings are:

- T_1 and MFR are the key variables determining the LR (lower T_1 and higher MFR increase it), while P_8 was fixed at 1.2 bar in all designs due to operational constraints.
- The feed compressor raises the LR from 15% (without the compressor, 45-bar feed) to 27.6% (P_6 = 90 bar); without it, the plant operates with zero power consumption, the return-gas compression work being supplied by the turboexpander. At 90 bar, the exergy efficiency is 61.8%, the COP_{eq} is 0.68, and the SPC is 160 kWh/t, and the economic functions improve (IRR = 38%, BEP = 2.4 years).
- With more than 270 operating days per year and a product price above 11 $/MMBtu, the IRR exceeds 30% and the BEP remains below 3 years; the base design remains justified even with 20% higher CAPEX (IRR = 32%), and the no-compressor case becomes viable with a 10% CAPEX reduction (IRR = 39%).

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