

Comprehensive Multi-Criteria Comparison and Ranking of Natural Gas Liquefaction Process by Analytic Hierarchy Process (AHP)

Hojat Ansarinasab ¹, Mahmoud Afshar ², Mehdi Mehrpooya ^{*3}

¹ Energy Systems Engineering department, Faculty of Mahmoud Abad,
Petroleum University of Technology, Mahmoud Abad, Iran

² Renewable Energies and Environment Department, Faculty of New Sciences and Technologies,
University of Tehran, Tehran, Iran

³ Hydrogen and fuel cell laboratory, Faculty of New Sciences and Technologies,
University of Tehran, Tehran, Iran

Abstract: Several processes have been proposed for natural gas liquefaction due to the vast utilization of LNG as a reliable and relatively easy to use fuel. Even though the merits and demerits of different process have been studied, a dearth of comprehensive technical and economical comparative investigation of these methods makes further broad examination a necessity. This article is presented to address this necessity. In this study, five different processes (MFC-Linde, DMR-APCI, C3MR-Linde, SMR-APCI, and SMR-Linde) were inclusively compared and ranked considering eight most relevant indices, namely power consumption, coefficient of performance, specific energy consumption, exergy efficiency, LNG production rate, refrigerant rate, number of equipment, and energy improvement potential. The comparison and ranking of these processes were carried out by analytic hierarchy process (AHP). The results indicated that DMR-APCI process was in the first rank. In this article, the variations of model resulted in change in the impact weight of each criterion and their effect on the aggregate priority of the alternative LNG processes was also assessed.

Keywords: Liquefied Natural Gas, LNG Process, Analytic Hierarchy Process, Ranking

1. Introduction

Energy is the most important element in the development of any society. Recently, natural gas has become more popular as an attractive energy source; however, its transfer to consumption locations is a challenging task. Liquefied natural gas (LNG) is easier to transfer and is more economical. LNG also constitutes the main reason of the development of natural gas liquefaction processes. Traditional LNG process included a propane pre-cooling step along with a mixed refrigerant step for gas liquefaction (C3MR). Today, technical advances and economic considerations have led to the emergence of

new processes. The new processes follow several goals such as overcoming limitations (e.g., string size), process efficiency, reducing investment costs, and better performance. Recently, natural gas liquefaction processes have attracted many researchers. Energy and exergy analyses method are used for five conventional liquefied natural gas processes (Vatani, Mehrpooya, & Palizdar, 2014b). Also, Exergy analysis of four small-scale liquefied natural gas processes was performed which showed that single mixed refrigerant (SMR) process had the best exergy efficiency (Remeljei & Hoadley, 2006). Additionally, Energy optimization in a liquefaction process by implementing genetic algorithm was carried

* Corresponding Author.

Authors' Email Address:

¹ Hojat Ansarinasab (h.ansarinasab@gmail.com), ² Mahmoud Afshar (mafshar@put.ac.ir),

³ Mehdi Mehrpooya (mehrpooya@ut.ac.ir)

out (Shirazi & Mowla, 2010). Exergy analysis of cascade refrigeration cycle used for natural gas liquefaction has also been reported to have a great potential for improvement (Kanoğlu, 2002). The analysis of PRICO liquefaction process including exergetic, exergoeconomic, and exergoenvironmental analysis have also been performed (Morosuk, Tesch, Hiemann, Tsatsaronis, & Omar, 2015). The results of these studies showed the possible options for improving the LNG process. Moreover, advanced exergy analysis was performed on five natural gas liquefaction processes (Vatani, Mehrpooya, & Palizdar, 2014a). Conventional and advanced exergy analyses is studied on a cascade refrigeration system for LNG process (Tsatsaronis & Morosuk, 2010). Exergoeconomic analysis is used in single mixed refrigerant natural gas liquefaction processes and sensitivity of exergy destruction cost, and exergoeconomic factor to the operating variables of such processes (Mehrpooya & Ansarinassab, 2015).

Selecting the best and the most suitable technology for gas liquefaction is a complex and very sensitive process which depends on many technical and economical design parameters. The technical parameters include power consumption, coefficient of performance, specific energy consumption, exergy efficiency, LNG production rate, refrigerant rate, and energy improvement potential. Economic issues include investment cost, performance cost, and lifecycle cost. To achieve an optimal LNG plant design, a comprehensive study including all relevant parameters is necessary and beneficial. Such a task is best performed by employing a multi-criteria decision-making method.

Analytic hierarchy process (AHP) method is one of the best and most accurate ranking and decision-making methods based on several indices (T. Saaty). It has been used for high energy related applications including wind observation location problem (Aras, Erdoğan, & Koç, 2004). A comprehensive decision-making analysis done with wind power integration projects based on improved fuzzy AHP and reported that the results attested to the feasibility of the method (Liu, Zhang, Liu, & Qian, 2012). A complete sustainability assessment process of coastal beach exploitation was presented by the analytic hierarchy process (AHP) (Tian, Bai, Sun, & Zhao, 2013). AHP model employed three dimensions of suitability, economic and social values, and ecosystem. Fuzzy AHP is used to select the best renewable energy alternatives in Indonesia (Tasri & Susilawati, 2014). Hydro

power was reported as the best renewable energy source, followed by geothermal, solar, wind energy, and biomass. AHP method was used to perform a comparison between the different electricity power generation options in Jordan (Akash, Mamlook, & Mohsen, 1999). In addition to fossil fuel power plants nuclear, solar, wind, and hydro-power plants were also considered. The results showed that solar, wind, and hydro-power might be the best alternatives.

AHP method was also used to select the best renewable energy sources for sustainable development of electricity generation system in Malaysia (Ahmad & Tahar, 2014) where four major resources, hydropower, solar, wind, biomass were considered. AHP model employed four main criteria, technical, economic, social and environmental aspects, and twelve sub-criteria. Furthermore, AHP model prioritized those resources, revealing that solar was the most favorable resource followed by biomass. AHP method was utilized to select space heating systems for an industrial building (Chinese, Nardin, & Saro, 2011). The results revealed that qualitative attributes also significantly affected industrial heating system choices and the AHP was effective in handling these aspects. Additionally, this method is applied to selecting the best solar thermal collection technology for electricity generation in north-west India (Nixon, Dey, & Davies, 2010). These technologies were compared based on technical, economic and environmental criteria. In the same vein, researchers used AHP to evaluate space heating systems running on conventional and renewable energy sources in Jordan (Jaber, Jaber, Sawalha, & Mohsen, 2008). Moreover, the prioritization of the low-carbon energy sources in China by using an AHP method supports this argument (Ren & Sovacool, 2015). In addition, AHP method was used for the prioritization of energy conservation policy instruments (Kablan, 2004).

In this article, the AHP method was employed to inclusively compare and prioritize five popular natural gas liquefaction processes (MFC-Linde, DMR-APCI, C3MR-Linde, SMR-APCI and SMR-Linde) considering eight technical and economic criteria. In this article, the variations of model resulted to change in the impact weight of each criterion and their effect on the aggregate priority of the alternative LNG processes were also assessed.

2. Process Description

Linde Company introduced a simple process for natural gas liquefaction with one refrigeration cycle namely Single Mixed Refrigerant processes (SMR) (Foeg, Bach, Stockman, Heiersted, & Fredheim, 1998). Capital costs of this process are low due to few number of components. Figure 1 shows the Schematic of SMR process by Linde Company. The refrigerant used in this process was a mixture of methane, ethane, propane, butane and nitrogen. This process consisted of three

compressor and four heat exchanger as main equipment.

The Air Products and Chemicals Inc. (APCI), presented another Single Mixed Refrigerant (SMR) process (Roberts, Agrawal, & Daugherty, 2002) with low equipment. Regarding to energy consumption viewpoint, SMR-APCI was better than SMR-Linde. Figure 2 shows the Schematic of SMR process by APCI Company. This process had only two heat exchangers with low capital cost.

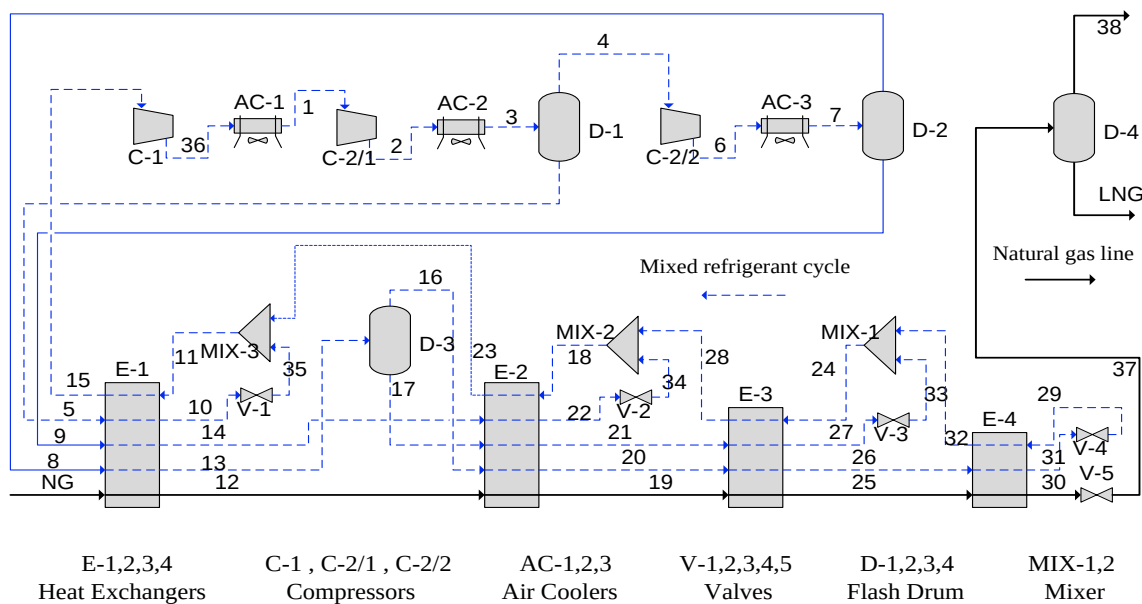


Figure 1. Schematic of SMR-Linde Process [6]

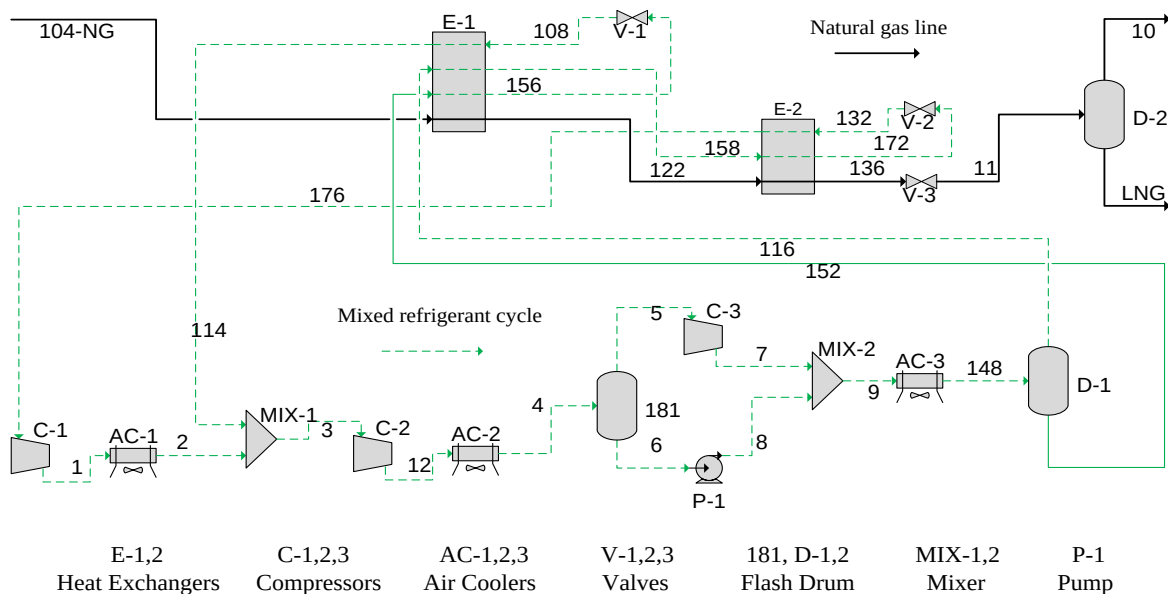


Figure 2. Schematic of SMR-APCI Process [6]

Linde Company in another patent (Foeg, et al., 1998) presented a process for natural gas liquefaction with two refrigeration cycle namely propane pre-cooled mixed refrigerant (C3MR) process. This process for pre-cooling uses pure propane but for liquefaction and sub-cooling uses mixed refrigerant as refrigerant. Schematic of C3MR process by Linde AG is shown in Figure 3. Unlike complexity this process, it was economical due to high efficiency.

The Double Mixed Refrigerant (DMR) is a process which in pre-cooling cycle uses mixed refrigerant unlike C3MR process that uses pure propane as refrigerant in pre-cooling cycle. APCI introduced a double mixed refrigerant process with a high efficiency (Roberts & Agrawal, 2001), as shown in

Figure 4. Two multi-stream heat exchangers (E-1 and E-2) were used for pre-cooling the natural gas in the first mixed refrigerant cycle, and two others heat exchangers (E-3 and E-4) were used for sub-cooling and liquefaction, respectively.

In another patent (Foeg, et al., 1998) a new high capacity LNG process called Mixed Fluid Cascade (MFC) which had three refrigeration cycles was presented by Linde AG and Stat oil. Because of three different mixed refrigerants used in each cycle, the energy efficiency of this process was high, which resulted in an increase of fixed cost and a decrease in operating costs, respectively. Figure 5 shows the Schematic of MFC process by Linde Company.

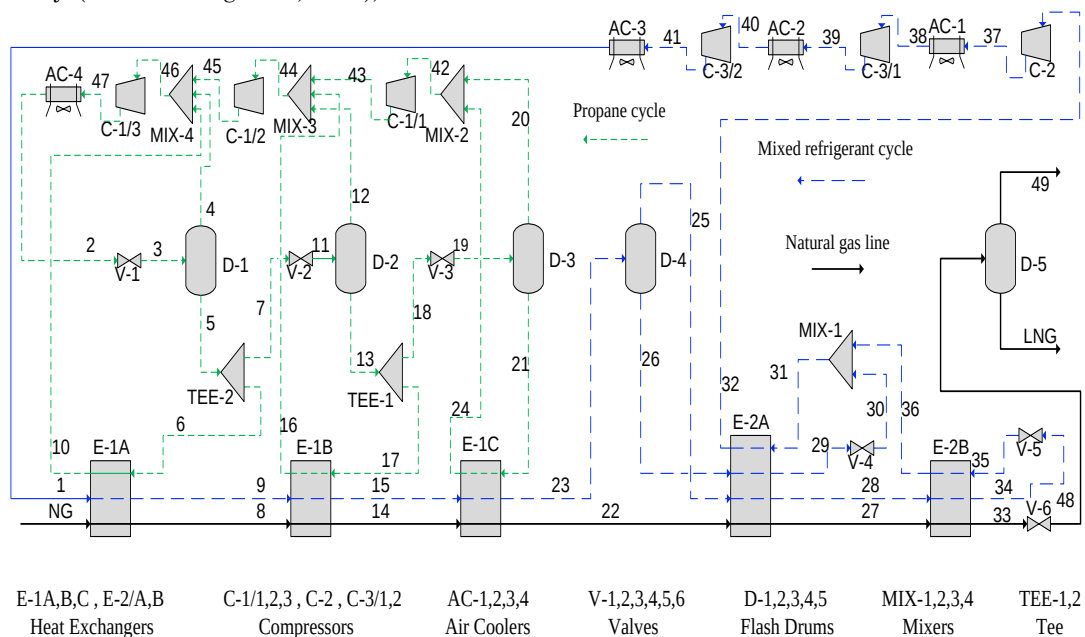


Figure 3. Schematic of C3MR-Linde Process [6]

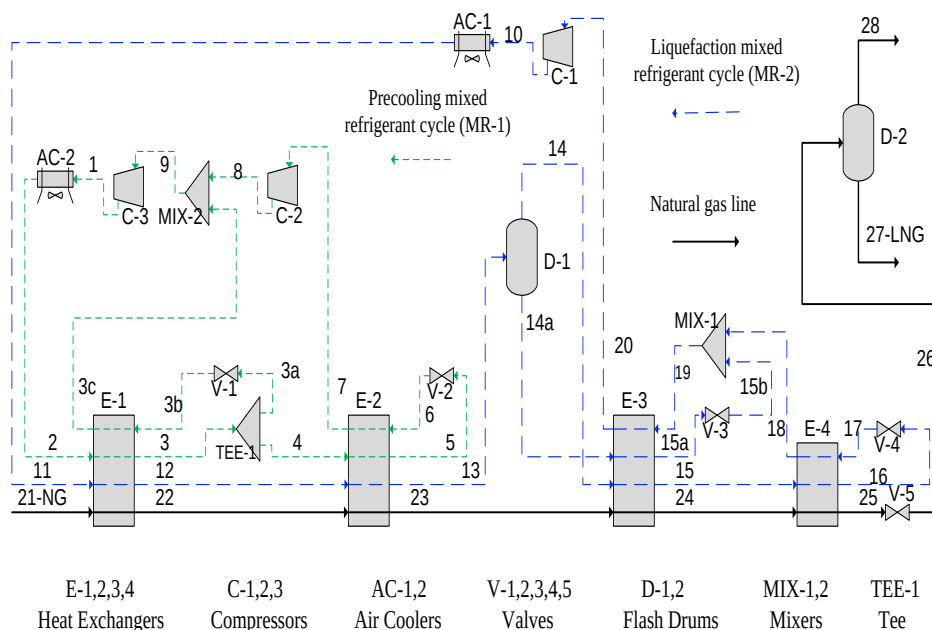


Figure 4. Schematic of DMR-APCI Process [6]

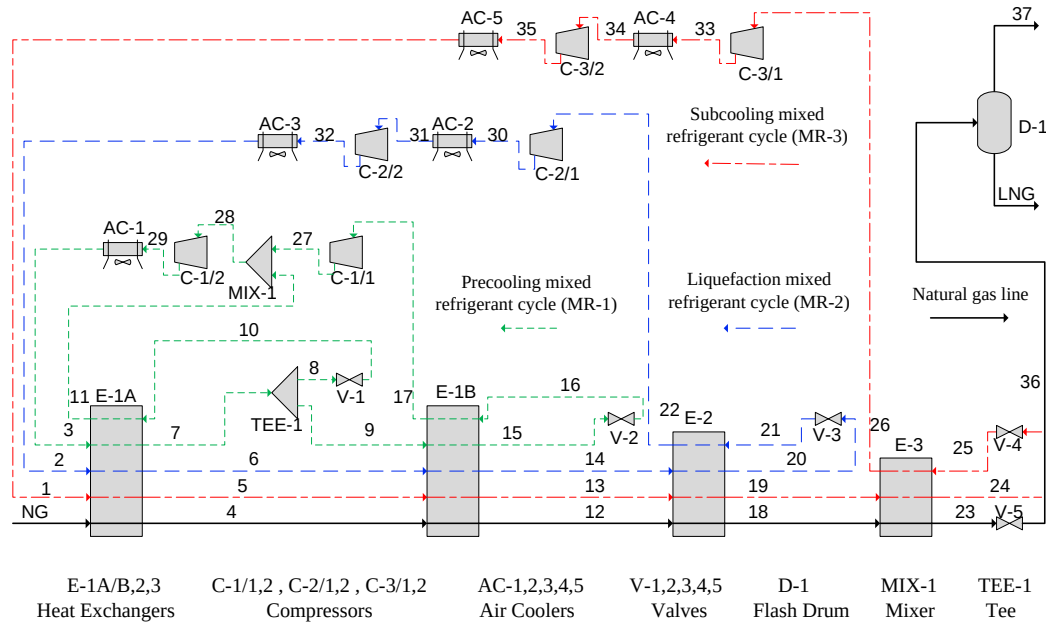


Figure 5. Schematic of MFC-Linde Process [6]

3. Processes Simulation

The first step in the analysis of these processes is modeling and simulation. In this article, the processes were simulated by Aspen HYSYS software ("Hypotech HYSYS v3.2 user guide," 2003). PRSV equation of state was possible to simulate a gas process (Vatani, et al., 2014a) due

to in this study PRSV was used for simulation in HYSYS. By simulation, different flow properties such as pressure, temperature, and flow rates were specified which were later required for energy and exergy analysis. The summary of the simulations results for selected streams of liquefaction processes are shown in Tables 1-5.

Table 1. Operating Conditions for SMR - Linde Process Streams [6]

Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)	Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)
NG	13.00	60.00	25120	6406159	20	-67.00	46.50	20673	5865177
1	35.00	9.00	61800	25897230	21	-67.00	46.50	20754	9472719
2	101.60	25.50	61800	25945237	22	-50.00	46.50	19564	10155839
3	35.00	25.50	61800	25935276	23	-34.94	3.00	60992	25384313
4	35.00	25.50	60992	25451274	24	-95.71	3.00	41428	15308913
5	35.00	25.50	807	484001	25	-93.00	60.00	25120	6429668
6	76.51	46.50	60992	25473396	26	-93.00	46.50	20673	5874119
7	35.00	46.50	60992	25465607	27	-85.00	46.50	20754	9476846
8	35.00	46.50	41428	15315628	28	-73.38	3.00	41428	15284340
9	35.00	46.50	19564	10149978	29	-162.80	3.00	20673	5893691
10	-1.00	25.50	807	484027	30	-161.00	60.00	25120	6459830
11	-34.89	3.00	61800	25868185	31	-156.00	46.50	20673	5896919
12	-3.00	60.00	25120	6406561	32	-95.52	3.00	20673	5836458
13	-3.00	46.50	41428	15317826	33	-98.34	3.00	20754	9472729
14	-3.00	46.50	19564	10150702	34	-66.22	3.00	19564	10151702
15	32.69	3.00	61800	25852544	35	-25.30	3.50	807	483904
16	-3.00	46.50	20673	5853510	36	100.20	9.00	61800	25906000
17	-3.00	46.50	20754	9464315	37	-164.00	1.01	25120	6455849
18	-70.90	3.00	60992	25435755	38	-164.00	1.01	1054	182957
19	-67.00	60.00	25120	6419984	LNG	-164.00	1.01	24065	6272892

Table 2. Operating Conditions for SMR-APCI Process Streams [6]

Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)	Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)
1	102.20	13.00	30395	10493201	108	-60.00	13.01	37504	18007903
2	32.00	13.00	30395	10489215	114	25.71	13.00	37504	17982409
3	25.27	13.00	67900	28468838	116	32.00	60.00	30395	10515294
4	32.31	27.10	67900	28496766	122	-52.50	66.50	27054	6690757
5	32.31	27.10	62300	25219866	132	-167.00	2.00	30395	10574795
6	32.31	27.10	62300	3277805	136	-153.80	66.50	27054	6736597
7	88.57	60.00	62300	25249905	148	32.00	60.00	67900	28515518
8	36.37	60.00	5600	3278257	152	32.00	60.00	37504	18000224
9	76.27	60.00	67900	28525910	156	-54.91	60.00	37504	18012756
10	-162.10	1.01	2043	434347	158	-21.00	60.00	30395	10519548
11	-162.10	1.01	27054	6731705	172	-164.30	60.00	30395	10581233
12	72.62	27.10	67900	28501807	176	-22.80	1.99	30395	10452957
104-NG	30.00	66.51	27054	6684612	LNG	-162.10	1.01	25011	6297357

Table 3. Operating Conditions for C3MR-Linde Process Streams [6]

Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)	Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)
NG	13.00	60.00	25120	6406159	26	-34.00	49.00	23955	9587775
1	35.00	49.00	33590	11813508	27	-128.00	60.00	25120	6442850
2	35.00	14.30	32000	19275116	28	-128.00	49.00	9634	2248487
3	1.63	5.00	32000	19272117	29	-128.00	49.00	23955	9613938
4	1.63	5.00	7963	4793903	30	-134.10	3.00	23955	9610293
5	1.63	5.00	24036	14478213	31	-133.00	3.00	33590	11838632
6	1.63	5.00	9133	5501721	32	-38.84	3.00	33590	11758656
7	1.63	5.00	14902	8976492	33	-161.00	60.00	25120	6459830
8	3.40	60.00	25120	406356	34	-161.00	49.00	9634	2255143
9	3.40	49.00	33590	11814737	35	-167.10	3.00	9634	2253763
10	19.07	5.00	9133	5497966	36	-131.50	3.00	9634	2228490
11	-19.37	2.50	14902	8975952	37	65.45	15.00	33590	11792105
12	-19.37	2.50	1953	1175280	38	35.00	15.00	33590	11790909
13	-19.37	2.50	12948	7800672	39	85.66	30.00	33590	11807776
14	-17.00	60.00	25120	6407251	40	35.00	30.00	33590	11804870
15	-17.00	49.00	33590	11817996	41	71.92	49.00	33590	11815467
16	-19.37	2.50	7251	4362272	42	-31.32	1.30	5697	3425130
17	-19.37	2.50	7251	4368376	43	-3.19	2.50	5697	3427119
18	-19.37	2.50	5697	3432295	44	-16.46	2.50	14902	8964612
19	-36.24	1.30	5697	3432158	45	14.54	5.00	14902	8970406
20	-36.24	1.30	537	322859	46	12.66	5.00	32000	19262221
21	-36.24	1.30	5160	3109299	47	63.70	14.30	32000	19283232
22	-34.00	60.00	25120	6408814	48	-164.00	1.01	25120	6455849
23	-34.00	49.00	33590	11822004	49	-164.00	1.01	1054	182957
24	-30.81	1.30	5160	3102271	LNG	-164.00	1.01	24065	6272892
25	-34.00	49.00	9634	2234228					

Table 4. Operating Conditions for DMR-APCI Process Streams [6]

Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)	Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)
1	85.98	19.20	23007	13273259	14a	-33.15	48.60	17678	7111287
2	36.85	19.20	23007	13264891	15	-128.40	48.60	7521	1768839
3	-0.05	19.20	23007	13265520	15a	-128.40	48.60	17678	7130862
3a	-0.05	19.20	13784	7947688	15b	-134.10	3.00	17678	7128226
3b	-2.86	7.60	13784	7947306	16	-160.10	48.60	7521	1773816
3c	34.61	7.60	13784	7943602	17	-166.60	3.00	7521	1772736
4	-0.05	19.20	9223	5317831	18	-135.10	3.00	7521	1754185
5	-33.15	19.20	9223	5319272	19	-133.60	3.00	25200	8882288
6	-36.22	2.80	9223	5318895	20	-40.20	3.00	25200	8821734
7	-4.88	2.80	9223	5309501	21-NG	26.85	65.00	18849	4684827
8	42.25	7.60	9223	5315164	22	-0.15	65.00	18849	4685118
9	37.68	7.60	23007	13258755	23	-33.15	65.00	18849	4686763
10	148.30	48.60	25200	8871725	24	-128.40	65.00	18849	4711910
11	31.85	48.60	25200	8862627	25	-160.10	65.00	18849	4724099
12	-0.15	48.60	25200	8863929	26	-166.00	1.01	18849	4720634
13	-33.15	48.60	25200	8868890	27-LNG	-166.00	1.01	17561	4531954
14	-33.15	48.60	7521	1757602	28	-166.00	1.01	1288	188679

Table 5. Operating Conditions for MFC-Linde Process Streams [6]

Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)	Stream no.	T (°C)	P (bar)	$\dot{m}$ (kmol/h)	$\dot{E}$ (kW)
NG	13.00	60.00	25120	6406159	20	-81.50	27.90	25700	11167063
1	35.00	33.90	18100	4580521	21	-92.09	3.10	25700	11164837
2	35.00	27.90	25700	11147916	22	-31.92	3.10	25700	11115291
3	35.00	16.90	34390	20785152	23	-162.00	60.00	25120	6460454
4	3.00	60.00	25120	6406367	24	-159.00	33.90	18100	4624157
5	3.00	33.90	18100	4580673	25	-166.20	3.50	18100	4622101
6	3.00	27.90	25700	11149906	26	-87.08	3.50	18100	4558483
7	8.80	16.90	34390	20785470	27	35.31	6.70	13756	8310837
8	8.80	16.90	20634	12471282	28	28.73	6.70	34390	20776976
9	8.80	16.90	13756	8314188	29	75.07	16.90	34390	20797602
10	-0.53	6.70	20634	12470605	30	62.68	15.00	25700	11140010
11	24.30	6.70	20634	12466175	31	35.00	15.00	25700	11139111
12	-27.00	60.00	25120	6408003	32	76.94	27.90	25700	11149834
13	-27.00	33.90	18100	4581658	33	57.72	25.00	18100	4577382
14	-27.00	27.90	25700	11155365	34	35.00	25.00	18100	4577062
15	-22.00	16.90	13756	8315740	35	63.03	33.90	18100	4580974
16	-29.58	3.00	13756	8315171	36	-164.30	1.01	25120	6456498
17	-1.41	3.00	13756	8304130	37	-164.30	1.01	922	156703
18	-85.20	60.00	25120	6427010	LNG	-164.30	1.01	24197	6299794
19	-85.20	33.90	18100	4597243					

4. Energy Analysis

Specific energy consumption (SEC), coefficient of performance (COP), and power consumption (PC) were the criteria for the LNG process ranking which were obtained by the energy analysis. Specific energy consumption was defined as the ratio of the energy used in the process in kWh to LNG produced in kg; coefficient of performance was the ratio of total heat removed from the gas to total work of the cycle and the power consumed was the power required by the process. These values, which have been obtained for different LNG processes of interest from the simulation results, are given in Table 6.

5. Exergy Analysis

Exergy analysis was used in cryogenics industry for improving the efficiency of process cycles by recognizing the effect of the efficiency of equipment on the general process. The equipment or cycles whose improvement is more beneficial to the process are specified. By adding cost, reliability, and environmental requirements data to this technique, a basic method is obtained for selecting and improving LNG plants. Conventional and advanced exergy analysis indices include exergy efficiency (EE) obtained from ordinary exergy analysis and energy improvement potential (EIP) obtained from advanced exergy analysis. The exergy destruction rate (Bejan & Tsatsaronis, 1996):

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \quad (1)$$

Where $\dot{E}_F$, $\dot{E}_P$ and $\dot{E}_D$ represent the fuel exergy, product exergy and exergy destruction rates, respectively.

The exergy efficiency is defined as (Bejan & Tsatsaronis, 1996):

$$EE = \frac{\dot{E}_P}{\dot{E}_F} \text{ or } EE = 1 - \frac{\dot{E}_D}{\dot{E}_F} \quad (2)$$

Advanced exergy analysis was performed based on the results of exergy analysis. The main idea of this analysis was to categorize the irreversibility or exergy destruction of the process components. Based on the removing ability, the exergy destruction was divided to two other parts:

- Avoidable exergy destruction
- Unavoidable exergy destruction

The unavoidable part of exergy destruction of the component presents a part which cannot be eliminated, even if the best available technologies are used. While avoidable part can

be eliminated through technical improvements of the process equipment. Energy improvement potential of each process is defined as ratio of total avoidable exergy destruction to total exergy destruction of process (Vatani, et al., 2014a):

$$EIP = \frac{\text{Total avoidable exergy destruction (kW)}}{\text{Total exergy destruction (kW)}} \quad (3)$$

The higher the EIP value, there is more potential for energy improvement of the process. Exergy efficiency values and potential improvement percentages in LNG processes are given in Table 6.

Competency should be completely evaluated in terms of lifecycle and heat efficiency. Type and amount of refrigerant used in a process are important indices of liquefaction cycles. If the refrigerant is provided from products of LNG plant, lifecycle should be taken into account in the calculation of total efficiency and evaluation of final cost. The investment made in the liquefaction plants should not violate cost effectiveness of the process: The number of equipment (NOE), as the major capital cost items, utilized in the process should be as low as possible. Another important index of liquefaction cycles is LNG production rate (LPR). LNG production rate, number of equipment and refrigerant rate (RR) of the LNG processes are given in Table 6.

6. AHP Method

One of the most wide spread used methods in multi-criteria decision making models is the analytical hierarchy process (AHP), introduced in 1970 by Saaty. AHP uses a hierarchical structure to represent a decision making problem, the first step is to build a graphical representation of the problem in which the goal, criteria and alternatives are indicated. Level one in the hierarchy indicates the goal, while the criteria and factors affecting the decision goal are set in the intermediate levels and the last level is the decision alternatives. As shown in Figure 6, the goal of interest, i.e. prioritization of the LNG processes, is located at the first layer, and evaluation criteria are located in the next layers, and the last level contains the LNG processes as the decision alternatives. Due to application of different computational methods in the second layer, the data in the second level do not have a uniform scale while values with the same scale is needed to make the comparison between the data. For this reason, the criteria were normalized to a common scale within the interval [0, 1] using the following relation:

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^J f_{ij}^2}} \quad (4)$$

Where r_{ij} is normalized value and f_{ij} is the value of the i th criterion function for alternative j th. The AHP normalized decision matrix is shown in Table 7.

Table 6. Criteria for Natural Gas Liquefaction Processes Selection (f_{ij})

Cycles	SEC (kWh/kg LNG)	PC (MW)	COP (--)	EE (%)	EIP (%)	LPR (kg/s)	NOE (--)	RR (kmol/h)
MFC-Linde	0.255	111.65	3.155	51.82	56.62	121.88	23	78190
DMR-APCI	0.275	87.34	2.694	47.78	42.13	88.35	19	48208
C3MR- Linde	0.271	118.33	2.219	50.98	53.19	121.23	32	65590
SMR-APCI	0.305	131.57	2.664	45.09	43.49	119.98	17	67900
SMR- Linde	0.357	155.90	2.218	40.20	48.29	121.23	22	61800

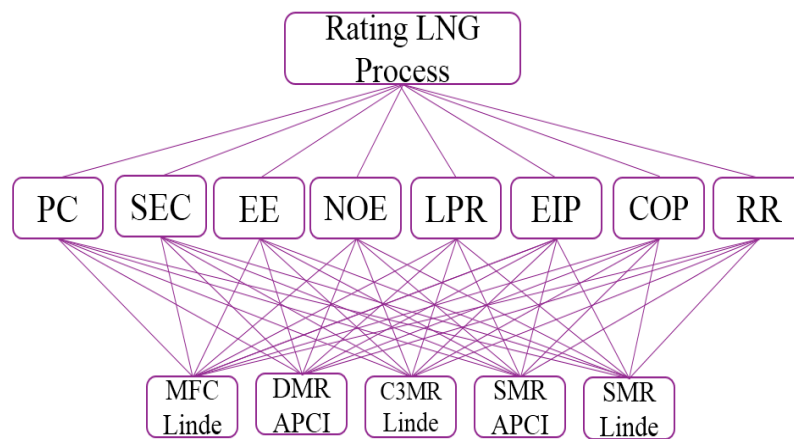


Figure 6. AHP Decision Hierarchy

Table 7. AHP Normalized Decision Matrix (r_{ij})

Cycles	SEC (kWh/kg LNG)	PC (MW)	COP (--)	EE (%)	EIP (%)	LPR (kg/s)	NOE (--)	RR (kmol/h)
MFC-Linde	0.386	0.406	0.539	0.489	0.516	0.473	0.444	0.537
DMR-APCI	0.417	0.317	0.461	0.451	0.384	0.343	0.366	0.331
C3MR- Linde	0.411	0.430	0.379	0.481	0.485	0.470	0.617	0.451
SMR-APCI	0.462	0.478	0.456	0.425	0.396	0.465	0.328	0.466
SMR- Linde	0.542	0.566	0.379	0.379	0.440	0.470	0.424	0.425

The implementation of the AHP method, involves the following steps (T. Saaty):

1- Pair comparison of decision elements and allocation of numeric values which indicates priority or importance between the two elements.

$$A = (a_{ij})_{m \times m} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{pmatrix} \quad (5)$$

where a_{ij} is the priority of the i th coefficient with respect to j th coefficient.

2- Elements of the pair comparison matrix A is then normalized using the following relation:

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{k=1}^m a_{kj}} \quad i, j = 1, 2, \dots, m \quad (6)$$

Then, the normalized pair comparison matrix $\bar{A}$ is obtained as:

$$\bar{A} = (\bar{a}_{ij})_{m \times m} \quad (7)$$

3- Numbers in each row in the matrix $\bar{A}$ are summed up:

$$\bar{\omega}_i = \sum_{j=1}^m \bar{a}_{ij} \quad i = 1, 2, \dots, m \quad (8)$$

Then, the weight vector $W = (\omega_1, \omega_2, \dots, \omega_m)$ is obtained from the following relation:

$$\omega_i = \frac{\bar{\omega}_i}{\sum_{k=1}^m \bar{\omega}_k} \quad i = 1, 2, \dots, m \quad (9)$$

Where, $\sum_{i=1}^m \omega_i = 1$

4- The maximum value of $\lambda_{\max}$ is obtained from the following equation:

$$\lambda_{\max} = \frac{1}{m} \sum_{i=1}^m \frac{(AW)_i}{\omega_i} \quad (10)$$

5- The consistency rate (CR) is obtained as the ratio of consistency index (CI) to random index (RI), RI figures for different values of m as suggested by (T. L. Saaty, 2000), are shown in Table 8. For obtaining RI parameter, square matrices ($n \times n$) with random entries but the properties of pairwise comparison matrices is formed then by calculating the average of the eigenvalues of mentioned matrices by computer RI parameter is obtained.

$$CR = \frac{CI}{RI} \quad (11)$$

Where,

$$CI = \frac{\lambda_{\max} - m}{m - 1} \quad (12)$$

If $CR < 0.1$, the pair comparison matrix has an acceptable consistency, but if $CR \geq 0.1$, the pair comparison matrix is inconsistent and the comparisons must be revised.

7. Results and Discussion

7.1. LNG Processes Prioritization

The results of AHP method employed on five alternative natural gas liquefaction processes (MFC-Linde, DMR-APCI, C3MR-Linde, SMR-APCI and SMR-Linde) were prioritized according to eight criteria, namely power consumption (PC), coefficient of performance (COP), specific energy consumption (SEC), exergy efficiency (EE), LNG production rate (LPR), refrigerant rate (RR), number of equipment (NOE) used in the process, and energy improvement potential (EIP) (Tables 9 to 16).

Regarding COP criterion, MFC process, with a priority factor equal to 0.243, had higher priority over other processes with DMR process in the second rank with a priority factor of 0.208 and SMR-Linde process in the last rank with a priority factor equal to 0.171. This shows that the MFC process had the highest performance among the processes investigated. AHP results for the COP criterion of natural gas liquefaction processes are presented in Table 9.

Table 8. RI Numbers for Different Values of m

Dimension	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Regarding PC criteria, DMR process had more favorable condition and stayed in the first rank with a priority factor of 0.267, while in the second rank was MFC process with a priority factor of 0.209, and in the last rank was SMR-Linde process due to its higher power demand compared to other processes. Therefore, in the places with limited power access, DMR process was the favorite process. AHP results for the PC criterion of natural gas liquefaction processes are presented in Table 10.

Considering EE criteria, MFC process took the first place with a priority factor of 0.220, while

in the second and fifth ranks are C3MR and SMR-Linde processes with priority factors of 0.203 and 0.170, respectively. AHP results for the EE criterion of natural gas liquefaction processes are presented in Table 11.

Regarding criteria NOE, SMR-APCI process was in the first rank due to its fewer number of equipment while C3MR process was in the last rank due to its highly complex process with larger number of equipment. AHP results for the NOE criterion of natural gas liquefaction processes are presented in Table 12.

Table 9. AHP Results for the COP Criterion of Natural Gas Liquefaction Processes

COP	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1.17	1.42	1.18	1.42	0.243
DMR	1/1.17	1	1.21	1.01	1.21	0.208
C3MR	1/1.42	1/1.21	1	1/1.20	1.01	0.172
SMR-APCI	1/1.18	1/1.01	1.20	1	1.20	0.206
SMR- Linde	1/1.42	1/1.21	1/1.01	1/1.20	1	0.171
$\lambda_{\max}=5.0000$, CI=0.0000, CR=0.0000 < 0.1						

Table 10. AHP Results for the PC Criterion of Natural Gas Liquefaction Processes

PC	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1/1.28	1.06	1.18	1.39	0.209
DMR	1.28	1	1.35	1.50	1.78	0.267
C3MR	1/1.06	1/1.35	1	1.20	1.32	0.2
SMR-APCI	1/1.18	1/1.50	1/1.20	1	1.18	0.175
SMR- Linde	1/1.39	1/1.78	1/1.32	1/1.18	1	0.15
$\lambda_{\max}=5.0007$, CI=0.00017, CR=0.00015 < 0.1						

Table 11. AHP Results for the EE Criterion of Natural Gas Liquefaction Processes

EE	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1.08	1.02	1.15	1.29	0.22
DMR	1/1.08	1	1/1.07	1.06	1.19	0.203
C3MR	1/1.02	1.07	1	1.15	1.27	0.217
SMR-APCI	1/1.15	1/1.06	1/1.15	1	1.12	0.19
SMR- Linde	1/1.29	1/1.19	1/1.27	1/1.12	1	0.17
$\lambda_{\max}=5.0001$, CI=0.00001, CR=0.00001 < 0.1						

Table 12. AHP Results for the NOE Criterion of Natural Gas Liquefaction Processes

NOE	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1/1.21	1.39	1/1.35	1/1.04	0.189
DMR	1.21	1	1.68	1/1.11	1.16	0.228
C3MR	1/1.39	1/1.68	1	1/1.5	1/1.45	0.142
SMR-APCI	1.35	1.11	1.5	1	1.29	0.244
SMR- Linde	1.04	1/1.16	1.45	1/1.29	1	0.197
$\lambda_{\max}=5.0059$, CI=0.0015, CR=0.0013 < 0.1						

According to RR criterion, DMR process has the highest rank because it used fewer refrigerant rates compared to other processes, while MFC process was in the last rank due to its great refrigerant rate. AHP results for the RR criterion of natural gas liquefaction processes are presented in Table 13.

MFC Process produces high LNG production rate, and therefore, its specific energy consumption (SEC) was lower than other processes and had more favorable condition,

while SMR-Linde process was in the last rank in terms of SEC criterion. AHP results for the RR criterion of natural gas liquefaction processes are presented in Table 14.

Considering EIP criteria, MFC process took the first place with a priority factor of 0.231, while in the second and fifth ranks were C3MR and DMR processes with priority factors of 0.224 and 0.173, respectively. AHP results for the EIP criterion of natural gas liquefaction processes are presented in Table 15.

Table 13. AHP Results for the RR Criterion of Natural Gas Liquefaction Processes

RR	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1/1.62	1/1.19	1/1.15	1/1.26	0.161
DMR	1.62	1	1.36	1.41	1.28	0.26
C3MR	1.19	1/1.36	1	1.2	1/1.06	0.197
SMR-APCI	1.15	1/1.41	1/1.2	1	1/1.1	0.179
SMR- Linde	1.26	1/1.28	1.06	1.1	1	0.203
$\lambda_{\max}=5.0026$, CI=0.00057, CR=0.00065 < 0.1						

Table 14. AHP Results for the SEC Criterion of Natural Gas Liquefaction Processes

SEC	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1.08	1.06	1.19	1.40	0.226
DMR	1/1.08	1	1/1.01	1.11	1.30	0.210
C3MR	1/1.06	1.01	1	1.20	1.32	0.216
SMR-APCI	1/1.19	1/1.11	1/1.20	1	1.17	0.187
SMR- Linde	1/1.40	1/1.30	1/1.32	1/1.17	1	0.161
$\lambda_{\max}=5.0005$, CI=0.00013, CR=0.00012 < 0.1						

Table 15. AHP Results for the EIP Criterion of Natural Gas Liquefaction Processes

EIP	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1.34	1.06	1.3	1.17	0.231
DMR	1/1.34	1	1/1.26	1/1.03	1/1.15	0.173
C3MR	1/1.06	1.26	1	1.40	1.10	0.224
SMR-APCI	1/1.30	1.03	1/1.40	1	1/1.11	0.174
SMR- Linde	1/1.17	1.15	1/1.10	1.11	1	0.198
$\lambda_{\max}=5.0022$, CI=0.00055, CR=0.00049 < 0.1						

Considering LPR criteria, MFC process took the first place with a priority factor of 0.213, while in the fifth ranks was DMR process with priority factor of 0.154. AHP results for the LPR criterion of natural gas liquefaction processes are presented in Table 16.

The result of AHP for prioritization of the natural gas liquefaction processes is shown in

Table 17. As shown, when all the criteria were simultaneously taken into consideration, DMR process had a relatively higher priority over the other processes and ranked the first with a priority equal to 0.231; while MFC, C3MR, SMR-APCI and SMR-Linde processes were ranked in the next places, respectively.

Table 16. AHP Results for the LPR Criterion of Natural Gas Liquefaction Processes

LPR	MFC	DMR	C3MR	SMR-APCI	SMR-Linde	Priorities
MFC	1	1.38	1.01	1/1.03	1.01	0.213
DMR	1/1.38	1	1/1.37	1/1.42	1/1.37	0.154
C3MR	1/1.01	1.37	1	1/1.02	1	0.212
SMR-APCI	1.03	1.42	1.02	1	1.04	0.209
SMR- Linde	1/1.01	1.37	1	1/1.04	1	0.212
$\lambda_{\max}=5.0017$, $CI=0.00043$, $CR=0.00038 < 0.1$						

Table 17. AHP Results for Prioritization of the Natural Gas Liquefaction Processes

Process	$\sum (\text{Local priority of alternative with respect to criteria}) \times (\text{Local priority of criteria with respect to goal})$	Rank
MFC	$(0.243 \times 0.125) + (0.209 \times 0.125) + (0.220 \times 0.125) + (0.231 \times 0.125) + (0.213 \times 0.125) + (0.189 \times 0.125) + (0.161 \times 0.125) + (0.226 \times 0.125) = 0.211$	2
DMR	$(0.208 \times 0.125) + (0.267 \times 0.125) + (0.203 \times 0.125) + (0.173 \times 0.125) + (0.154 \times 0.125) + (0.228 \times 0.125) + (0.260 \times 0.125) + (0.210 \times 0.125) = 0.213$	1
C3MR	$(0.172 \times 0.125) + (0.200 \times 0.125) + (0.217 \times 0.125) + (0.224 \times 0.125) + (0.213 \times 0.125) + (0.142 \times 0.125) + (0.197 \times 0.125) + (0.216 \times 0.125) = 0.197$	3
SMR-APCI	$(0.206 \times 0.125) + (0.175 \times 0.125) + (0.190 \times 0.125) + (0.174 \times 0.125) + (0.209 \times 0.125) + (0.244 \times 0.125) + (0.179 \times 0.125) + (0.187 \times 0.125) = 0.195$	4
SMR-Linde	$(0.171 \times 0.125) + (0.150 \times 0.125) + (0.170 \times 0.125) + (0.198 \times 0.125) + (0.212 \times 0.125) + (0.197 \times 0.125) + (0.203 \times 0.125) + (0.161 \times 0.125) = 0.183$	5

7.2. Criterion Impact Weight Alterations Analysis

To this point, it was assumed that all criteria had equal impact or significance on the LNG plants different processes overall performance. However, there were many instances in which one of this criterion had a greater impact on the LNG processes, because of technical, geographical, energy source and other limitations on the site. Therefore, in this section, the changes in the importance of each criterion on the LNG processes ranking, which was labeled as impact weight, was investigated. Also it should be noted that this a different weight to what was used in the previous section as the process priority factors to prioritize different LNG processes.

As shown in Figure 7, axes X and Y show the criterion's impact weight and alternative's LNG processes priority factors, respectively. For example when that weight of COP was zero, (this means that the COP criterion had removed and the number of criteria has got to 7), weight of other criteria were the same and equal to $(1/7=0.143)$. Also, when that weight of COP was one, (This means that the ranking was done only on the basis of COP criterion and the other criteria had removed), weight of other criteria were the same and equal to zero. The vertical dashed line on X axis indicated the location of the impact weight in the previous section analysis, in which all criteria impact

weights were the same and equal to $(1/8=0.125)$.

Responses of the LNG processes to the variation in impact weight of criterion COP are shown Figure 7. As shown, by a 20% increase and decrease in the impact weight of criterion COP, the order of prioritization did not change; however, by a 30% increase or more in the impact weight of criterion COP, DMR and C3MR were respectively replaced by alternatives MFC Linde and SMR-APCI processes. MFC-Linde process showed the highest sensitivity, while DMR-APCI process had the lowest sensitivity to variation in the impact weight of criterion COP, also no increases or decreases was seen in the ranking of SMR-Linde process.

The rankings alterations of the alternatives process by the variation in impact weight of criterion PC is shown in Figure 8. As shown in the figure, by increasing the impact weight of criterion PC, no change in the prioritization of alternatives was observed; however, a 30% decrease in the impact weight of criterion PC, the rankings of the alternatives DMR and C3MR were respectively replaced by alternatives MFC and SMR-APCI processes. DMR process had the highest sensitivity, while MFC and C3MR processes has the lowest sensitivity to the variation in the impact weight of criterion PC, also, no increases or decreases was seen in the ranking of the SMR-Linde process.

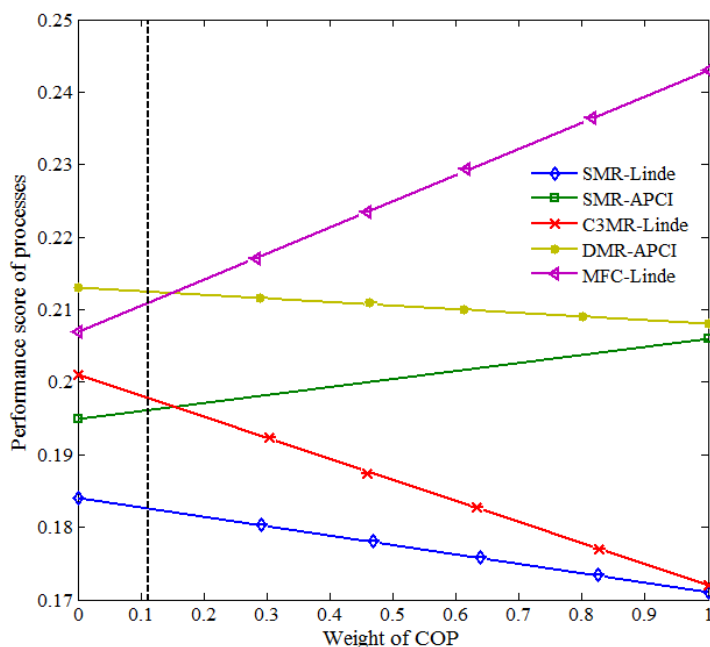


Figure 7. Variations in Performance Score of LNG Pocesess with Respect to Weight of COP

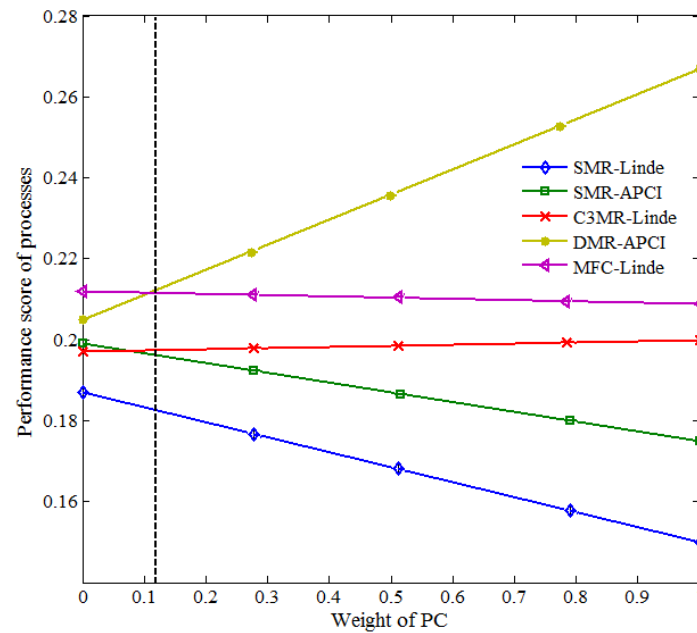


Figure 8. Variations in Performance Score of LNG Processes with Respect to Weight of PC

The rankings alterations of the alternatives process by the variation in impact weight of criterion EE is shown in Figure 9. As shown in the figure, by a 20% increase or decrease in the impact weight of criterion EE, no change in the prioritization of alternative processes was observed; but by a 30% increase in the impact weight of criterion EE, alternative process DMR was ranked after alternative processes MFC and C3MR, also, no increases or decreases was seen in the ranking of the SMR-Linde process.

The rankings alterations of the alternatives process by the variation in impact weight of criterion EIP is shown in Figure 10. As shown in the figure, by a 30% decrease in the impact weight of criterion EIP, alternative process SMR-APCI would have a higher rank than alternative process C3MR. Alternative process DMR had higher sensitivity to the criterion EIP and when the weight of criterion EIP is 0.15, 0.23, 0.6, and 0.96, the rank of this alternative was replaced by alternatives MFC, C3MR, SMR-Linde and SMR-APCI processes, respectively.

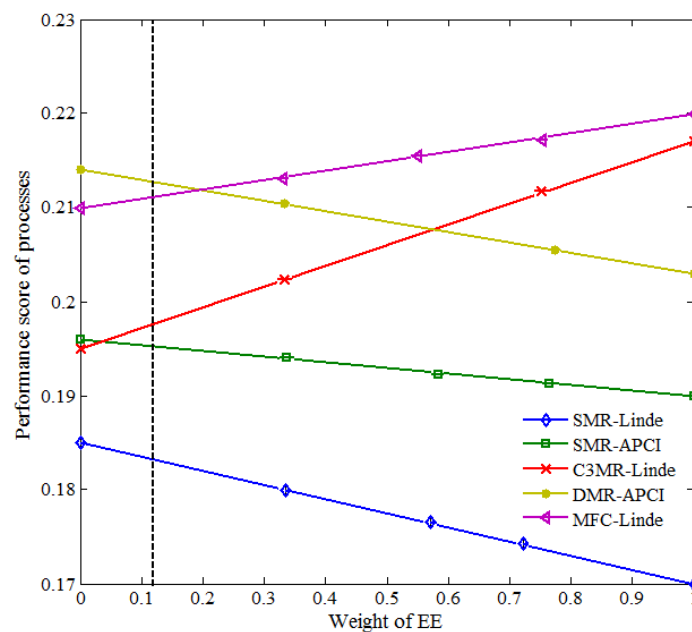


Figure 9. Variations in Performance Score of LNG Processes with Respect to Weight of EE

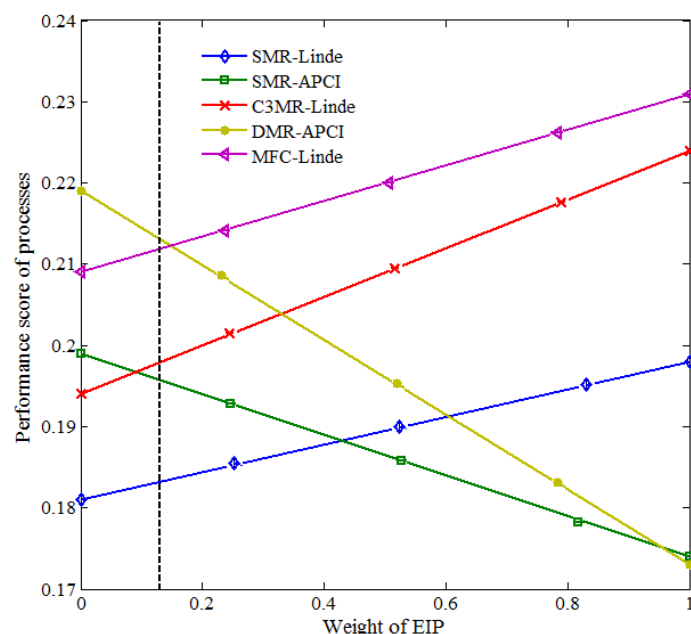


Figure 10. Variations in Performance Score of LNG Processes with Respect to Weight of EIP

The rankings alterations of the alternatives process by the variation in impact weight of criterion LPR is shown in Figure 11. As shown in the figure, by decreasing the impact weight of criterion LPR, no change in the prioritization of alternatives was observed. Alternative process DMR has higher sensitivity to criterion LPR and when the impact weight of criterion LPR was 0.14, 0.3, 0.34, and 0.42, this alternative was replaced by alternatives MFC, C3MR, SMR- APCI and SMR- Linde processes, respectively.

The rankings alterations of the alternatives process by the variation in impact weight of criterion NOE is shown in Figure 12. As shown in the figure, by a 20% decrease in the impact weight of criterion NOE, alternative process DMR exchange its rank with alternative process MFC, and by a 20% increase in the impact weight of criterion NOE, alternative process C3MR ranking was replaced by alternative process SMR-APCI.

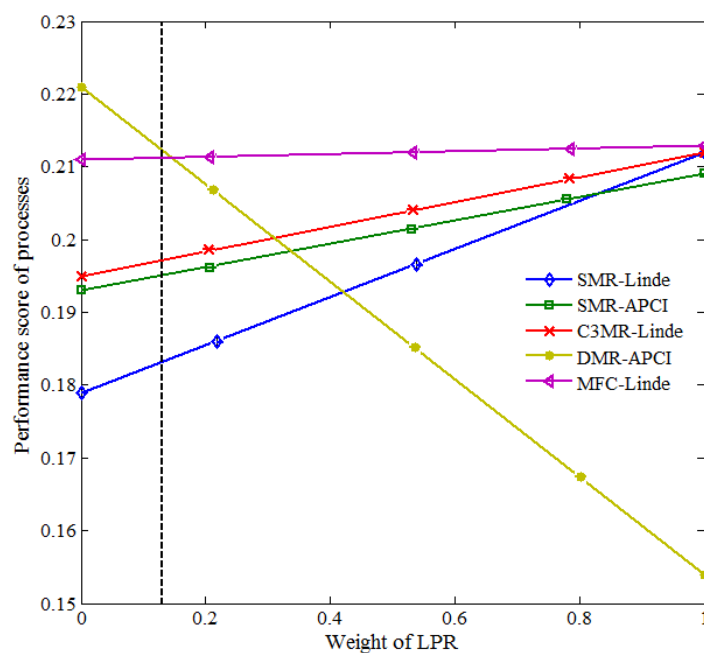


Figure 11. Variations in Performance Score of LNG Processes with Respect to Weight of LPR

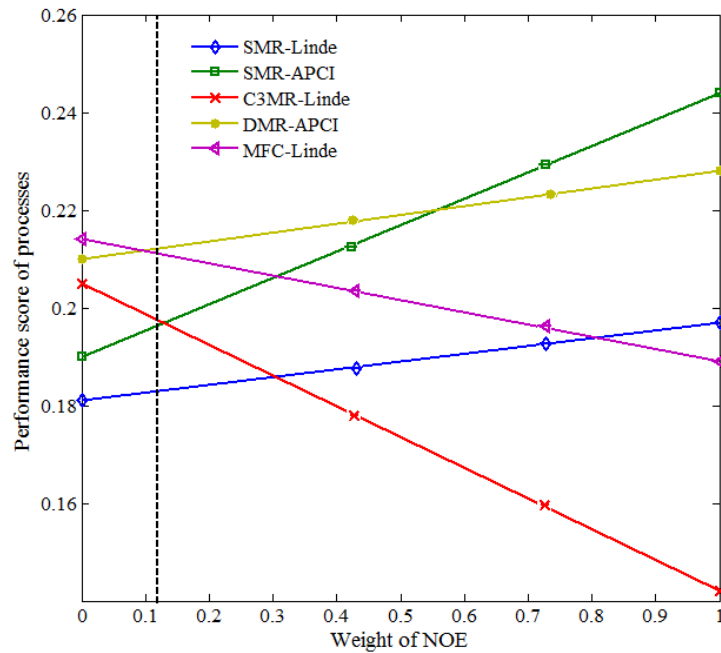


Figure 12. Variations in Performance Score of LNG Processes with Respect to Weight of NOE

The rankings alterations of the alternatives process by the variation in impact weight of criterion RR is shown in Figure 13. As shown in the figure, by a 20% decrease in the impact weight of criterion RR, alternative process MFC was in the first rank, while alternative DMR was in the second rank. Moreover, alternatives processes DMR and MFC had the highest sensitivity to this criterion.

The rankings alterations of the alternatives process by the variation in impact weight of

criterion SEC is shown in Figure 14. As shown in the figure, decreasing the impact weight of criterion SEC to 0.06 causes a change in the ranks of alternatives processes C3MR and SMR-APCI, and when the weight of criterion SEC is 0.21 and 0.79, alternative process DMR was replaced by alternatives MFC and C3MR processes, respectively, also, no increases or decreases was seen in the ranking of the SMR-Linde process

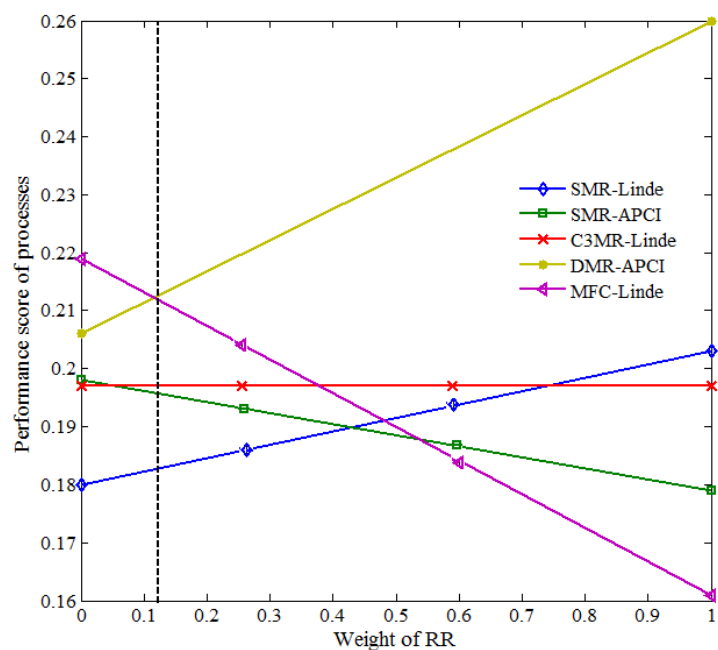


Figure 13. Variations in Performance Score of LNG Processes with Respect to Weight of RR

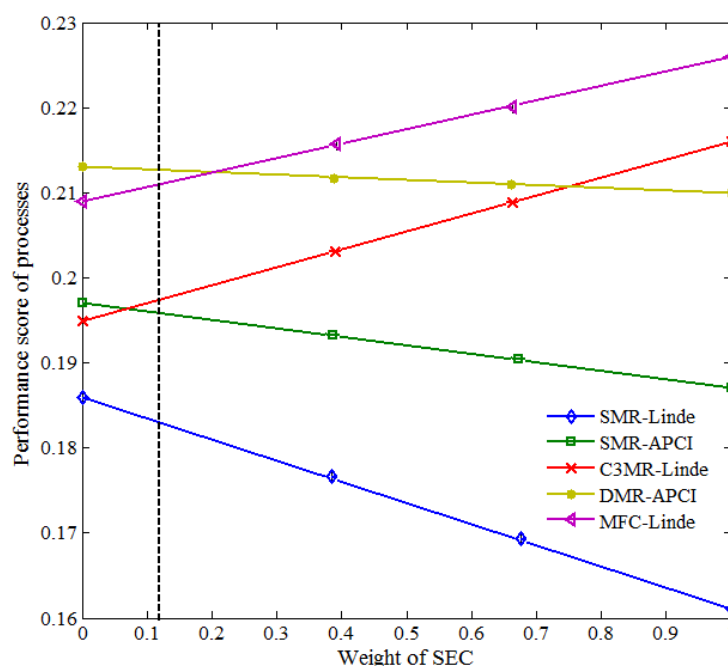


Figure 14. Variations in Performance Score of LNG Processes with Respect to Weight of SEC

8. Conclusion

Considering the increased demand for LNG, and therefore, the greater interest in a more efficient natural gas liquefaction process, and availability of several innovative LNG processes; in this paper a comprehensive technical and economical multi-criteria AHP priority analysis was performed to rank these natural gas liquefaction processes: MFC-Linde, DMR-APCI, C3MR-Linde, SMR-APCI and SMR-Linde. The analysis and prioritization were carried out based on the eight criteria, namely: PC, COP, SEC, EE, LPR, RR, NOE and EIP. We found the following conclusions:

- Among the investigated processes, DMR process had a relatively higher priority over other processes and took the first rank with a priority factor equal to 0.213; while MFC, C3MR, SMR-APCI and SMR-Linde processes respectively took the next priorities.
- Considering specific constraints in LNG plants around the world, which influenced the impact of different criteria in this analysis, a criterion impact weight alterations analysis was also carried out to present the changes in the priorities of these LNG processes versus the changes in the impact of each criterion. The latter analysis would be quite helpful for the sites with possible constraints that could affect the impact factors.
- Overall, considering different technical and economical situations in different places around the world, the use of AHP multi-

criteria analysis proved to be quite useful for selection of the best natural gas liquefaction process matching specific site conditions.

Nomenclature

CI	Consistency index
CR	Consistency rate
r_{ij}	normalized evaluation matrix
RI	Random index
W	Eigen vector
<i>Greek Letters</i>	
λ_{max}	Eigen value
<i>Subscripts</i>	
D	Destruction
F	Fuel
P	Production
<i>Abbreviations</i>	
AC	Air Cooler
AHP	Analytic Hierarchy Process
APCI	Air Products and Chemicals, Inc.
C	Compressor
COP	Coefficient Of Performance
C3MR	C3 Precooled MR
D	Flash Drum
DMR	Dual Mixed Refrigerant
E	Multi Stream Heat Exchanger
$\dot{E}$	Exergy rate (kW)
EE	Exergy Efficiency
EIP	Energy Improvement Potential
LNG	Liquefied Natural Gas

LPR	LNG Production Rate
MFC	Mixed Fluid Cascade
MIX	Mixer
MR	Mixed Refrigerant
NG	Natural Gas
NOE	Number Of Equipment
P	Pump
RR	Refrigerant Rate
SMR	Single Mixed Refrigerant
SEC	Specific Energy Consumption
V	Expansion Valve

References

- Ahmad, S., & Tahar, R. M. (2014). Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. *Renewable Energy*, 63, 458-466.
- Akash, B. A., Mamlook, R., & Mohsen, M. S. (1999). Multi-criteria selection of electric power plants using analytical hierarchy process. *Electric Power Systems Research*, 52(1), 29-35.
- Aras, H., Erdoğan, Ş., & Koç, E. (2004). Multi-criteria selection for a wind observation station location using analytic hierarchy process. *Renewable Energy*, 29(8), 1383-1392.
- Bejan, A., & Tsatsaronis, G. (1996). *Thermal design and optimization*: John Wiley & Sons.
- Chinese, D., Nardin, G., & Saro, O. (2011). Multi-criteria analysis for the selection of space heating systems in an industrial building. *Energy*, 36(1), 556-565.
- Foeg, W., Bach, W., Stockman, R., Heiersted, R., & Fredheim, A. (1998). A new LNG base load process and the manufacturing of the main heat exchangers. *Proceedings of the LNG*, 12, 4.
- Hyprotech HYSYS v3.2 user guide. (2003). *Aspen Technology Inc., Burlington, MA*.
- Jaber, J., Jaber, Q., Sawalha, S., & Mohsen, M. (2008). Evaluation of conventional and renewable energy sources for space heating in the household sector. *Renewable and Sustainable Energy Reviews*, 12(1), 278-289.
- Kablan, M. (2004). Decision support for energy conservation promotion:: an analytic hierarchy process approach. *Energy policy*, 32(10), 1151-1158.
- Kanoğlu, M. (2002). Exergy analysis of multistage cascade refrigeration cycle used for natural gas liquefaction. *International Journal of Energy Research*, 26(8), 763-774.
- Liu, S., Zhang, J., Liu, W., & Qian, Y. (2012). A comprehensive decision-making method for wind power integration projects based on improved fuzzy AHP. *Energy Procedia*, 14, 937-942.
- Mehrpooya, M., & Ansarinassab, H. (2015). Exergoeconomic evaluation of single mixed refrigerant natural gas liquefaction processes. *Energy Conversion and Management*, 99, 400-413.
- Morosuk, T., Tesch, S., Hiemann, A., Tsatsaronis, G., & Omar, N. B. (2015). Evaluation of the PRICO liquefaction process using exergy-based methods. *Journal of Natural Gas Science and Engineering*, 27, 23-31.
- Nixon, J., Dey, P., & Davies, P. (2010). Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the analytical hierarchy process. *Energy*, 35(12), 5230-5240.
- Remelje, C., & Hoadley, A. (2006). An exergy analysis of small-scale liquefied natural gas (LNG) liquefaction processes. *Energy*, 31(12), 2005-2019.
- Ren, J., & Sovacool, B. K. (2015). Prioritizing low-carbon energy sources to enhance China's energy security. *Energy Conversion and Management*, 92, 129-136.
- Roberts, M. J., & Agrawal, R. (2001). Dual mixed refrigerant cycle for gas liquefaction: Google Patents.
- Roberts, M. J., Agrawal, R., & Daugherty, T. L. (2002). Single mixed refrigerant gas liquefaction process: Google Patents.
- Saaty, T. The Analytic Hierarchy Process, McGraw-Hill, New York, 1980. *There is no corresponding record for this reference*.
- Saaty, T. L. (2000). *Fundamentals of decision making and priority theory with the analytic hierarchy process* (Vol. 6): Rws Publications.
- Shirazi, M. M. H., & Mowla, D. (2010). Energy optimization for liquefaction process of

- natural gas in peak shaving plant. *Energy*, 35(7), 2878-2885.
- Tasri, A., & Susilawati, A. (2014). Selection among renewable energy alternatives based on a fuzzy analytic hierarchy process in Indonesia. *Sustainable Energy Technologies and Assessments*, 7, 34-44.
- Tian, W., Bai, J., Sun, H., & Zhao, Y. (2013). Application of the analytic hierarchy process to a sustainability assessment of coastal beach exploitation: A case study of the wind power projects on the coastal beaches of Yancheng, China. *Journal of environmental management*, 115, 251-256.
- Tsatsaronis, G., & Morosuk, T. (2010). Advanced exergetic analysis of a refrigeration system for liquefaction of natural gas. *International Journal of Energy and Environmental Engineering*, 1(1), 1-18.
- Vatani, A., Mehrpooya, M., & Palizdar, A. (2014a). Advanced exergetic analysis of five natural gas liquefaction processes. *Energy Conversion and Management*, 78, 720-737.
- Vatani, A., Mehrpooya, M., & Palizdar, A. (2014b). Energy and exergy analyses of five conventional liquefied natural gas processes. *International Journal of Energy Research*, 38(14), 1843-1863.