ENHANCING THE THERMODYNAMIC PERFORMANCE OF A STEAM POWER PLANT THROUGH THE UTILIZATION OF COLD EXERGY

Giuma M. Fellah and Yaeqoub O. Wanteeni

Department of Mechanical and Industrial Engineering, Faculty of Engineering
University of Tripoli, Libya
Email: g.fellah@uot.edu.ly
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الملخص

يهدف هذا العمل إلى المساهمة في استرجاع الإكسيرجي الباردة من الحالات ذات درجات الحرارة المنخفضة وتطوير نظام هجين يستخدم الإكسيرجي الباردة لتحسين الأداء الحراري لمحطة قدرة كهربائية. تحتوي المواد في درجات حرارة أقل من درجة حرارة المحيط الجوي، مثل الغاز الطبيعي المسال، على كمية كبيرة من الإكسيرجي الباردة، والتي غالباً ما يتم تجاهلها ولا يتم استردادها أثناء عملية التغويز. يتم ضغط الغاز الطبيعي وتسييله لتقليل حجمه المحدد للشحن بشكل كبير، حيث تصل درجات الحرارة إلى مستويات منخفضة للغاية تبلغ حوالي 110 كلفن. الحرارة الكامنة للميثان، المكون الأساسي للغاز الطبيعي، عند 0.1 ميجا باسكال هي 512 كيلو جول/كجم. يمكن استرداد الإكسيرجي الباردة عن طريق نقل الحرارة من مصدر خارجي، مثل مياه البحر، إلى محرك حراري أثناء طرد الحرارة إلى خزان حراري مثل الغاز الطبيعي المسال أثناء عملية التبخر. تم اختيار محطة درنة للطاقة البخارية كدراسة حالة للاستفادة من الإكسيرجي الباردة من الغاز الطبيعي المسال. نتيجة لذلك، يتم زيادة صافي إنتاج القدرة، وكفاءة القانون الأول، والكفاءة الإكسيرجية بنسبة 22.73٪.

ABSTRACT

The main objective of this work is to contribute to the recovery of cold exergy from low-temperature states and to develop a hybrid system that utilizes this exergy to enhance the thermal performance of an electrical power plant. Materials at temperatures lower than atmospheric temperature, such as liquefied natural gas (LNG), contain a significant amount of cold exergy, which is often overlooked and not recovered during the regasification process. Natural gas is compressed and liquefied to significantly reduce its specific volume for shipping, reaching extremely low temperatures of around 110 K. The latent heat of methane—the primary component of natural gas—at 0.1 MPa is 512 kJ/kg. Cold exergy can be recovered by transferring heat from an external source, such as seawater, to a heat engine while rejecting heat to a sink, such as LNG, during the evaporation process. Derna steam power plant is selected as a case study for utilizing the cold exergy from liquefied natural gas; as a result, the net power output, first law efficiency, and exergetic efficiency are increased by 22.73%.

KEYWORDS: Exergy; Cold exergy, liquefied natural gas; re-gasification.

INTRODUCTION

The rising global energy demand, driven by population growth and technological advancements, is correlated with an escalation in pollutant emissions. Natural gas (NG) could be considered the best choice for powering electrical power plants due to its low carbon intensity and high conversion efficiency. Natural gas is compressed to about $1/600^{th}$ of its original volume and cooled to approximately -162 °C to be converted into liquefied natural gas (LNG) for transportation, storage, and shipping to power plant siteThe production of NG has increased since the economic crisis in 2009 to about 3,613×10^9 m^3. As a result, the liquefaction and transportation of natural gas are expected to increase significantly in the upcoming years. Although the liquefaction of natural gas (NG) is an energy-intensive process, the liquefied natural gas (LNG) retains a significant amount of cold exergy. At the end-user site, the LNG is regasified to power the electrical power plant. A significant amount of cold exergy of about 370 kJ/kg is released and not recovered during the regasification process [1].

In the context of conventional regasification, the exergy inherent in liquefied natural gas (LNG) is often destroyed. Numerous researchers have highlighted the potential for harnessing the cold exergy of LNG. The cold energy generated during the regasification of LNG can be effectively utilized as a heat sink within a power cycle, employing ambient or waste heat as the primary heat source [2].

There are different ways to use the cold energy from LNG regasification in power generation. Researchers have suggested several methods, including: (i) directly expanding LNG; (ii) using LNG as a cooling source for Rankine power plants [3].

The projected energy mix for the future indicates that while growth rates for renewable energy sources are expected to be the highest, fossil fuels will continue to dominate in absolute terms. Among these, natural gas stands out as the most appealing option due to its favourable environmental impact.[4]. For instance, the Government of Indonesia is planning to construct a liquefied natural gas (LNG) receiving terminal to supply a power plant in Gresik. The total LNG to be regasified at the terminal is 54.23 tons per hour of natural gas [5]

The first liquefaction of natural gases took place in 1910, isolating ethane and propane from natural gas for sale. Until the 1950s, many plans were made to transport LNG overseas, and the first liquefied methane was shipped abroad by the Methane Pioneer, an LNG carrier, in 1959. Today, about 30 countries operate natural gas liquefaction plants [6].

MATERIALS AND METHODS

Exergy and exergy analysis serve as critical instruments for the development and sustenance of a sustainable civilization. Exergy analyses have been employed to evaluate the utilization of natural gas by various countries. Furthermore, exergy analysis facilitates the examination of the conversion processes of energy from resources to their final applications [7]. In this section, the basis of cold exergy, the governing equations, together with the chosen steam power plant, regasification cycle, and hybrid power plant, are presented.

The Basis of Cold Exergy

Cold exergy is recognized when the temperature of a given substance is lower than the reference temperature, typically taken as the standard atmospheric temperature of 25°C. Depending on the temperatures of the substance and the surrounding atmosphere, the transfer of exergy and heat may occur in the same or opposite directions. This concept can be further clarified as follows: When a given state has a temperature higher than the atmospheric temperature, as shown in Figure (1), the exergy flow rate is determined by the following equation [8]:

$$\dot{\Psi}_Q = \dot{Q}_H\left(1 - \frac{T_0}{T}\right) \quad for \;\; T > T_0 \tag{1}$$

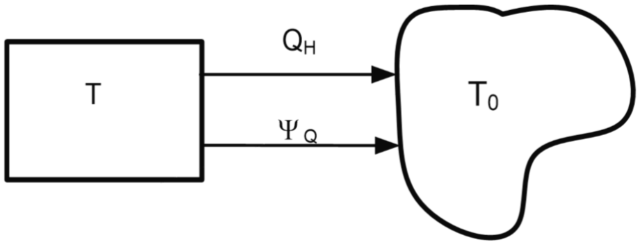

Figure 1: The flow direction of heat and exergy for T greater than T_0.

The heat transfer from the system is assigned a negative sign. Since T is greater than T_0, the term $(1-T_0/T)$ is positive. Consequently, the exergy flow follows the same direction as the heat flow. In other words, when the system's temperature T is higher than the reference temperature T_0, its exergy decreases as heat is transferred from the system to its surroundings. The exergy factor is defined by [8]:

$$f_{ex} = \frac{\dot{\Psi}_Q}{\dot{Q}_H} = \left|1 - \frac{T_0}{T}\right| \tag{2}$$

As observed, since the exergy factor is less than one, the exergy flow rate is lower than the heat flow rate, that is $\dot{\Psi}_Q < \dot{Q}_H$.

When the given state is at a temperature lower than the atmospheric temperature, see Figure (2), the exergy flow rate is given by [8]:

$$\dot{\Psi}_Q = \dot{Q}_C\left(1 - \frac{T_0}{T}\right) \; for \;\; T < T_0 \tag{3}$$

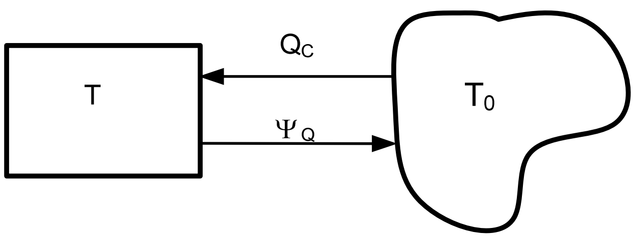

Figure 2: The flow direction of heat and exergy for T smaller than T_0.

Heat or cold flow into the system is assigned a positive sign. For extremely low temperatures (typically below 123 K, referred to as 'cryogenic,' where 'cold' is used instead of 'heat'), if T is lower than T_0, the term $(1-T_0/T)$ becomes negative. As a result, the exergy flow is in the opposite direction of the heat flow. In other words, when the system's temperature T is lower than the reference temperature T_0, its exergy decreases as heat is transferred into the system from the surroundings. The exergy factor is given by:

$$f_{ex} = \frac{\dot{\Psi}_Q}{\dot{Q}_C} = \left|1 - \frac{T_0}{T}\right| \tag{4}$$

When the exergy factor is greater than one, the exergy flow exceeds the heat flow. This implies that the system has a higher potential to perform useful work relative to the amount of heat transferred, then if:

$$\left|1 - \frac{T_0}{T}\right| > 1$$

or

$$\frac{T_0}{T} - 1 > 1$$

then

$$\frac{T_0}{T} > 2 \quad or: \frac{T}{T_0} < 0.5$$

Figure (3) shows the variation of the exergy factor with T/T_0. As can be seen, the flow of exergy is greater than the flow of heat if and only if T/T_0 is less than 0.5, the result, is considered one of the most important advantages of utilizing exergy at temperatures lower than the reference temperature. As we approach absolute zero, the value of the exergy factor tends toward infinity. The exergy factor equals zero when the system temperature and reference temperatures are equal, in this case there is no flow of heat or exergy. Also, it can be seen the flow of heat is greater than the flow of exergy when the temperature ratio T/T_0 is greater than 0.5.

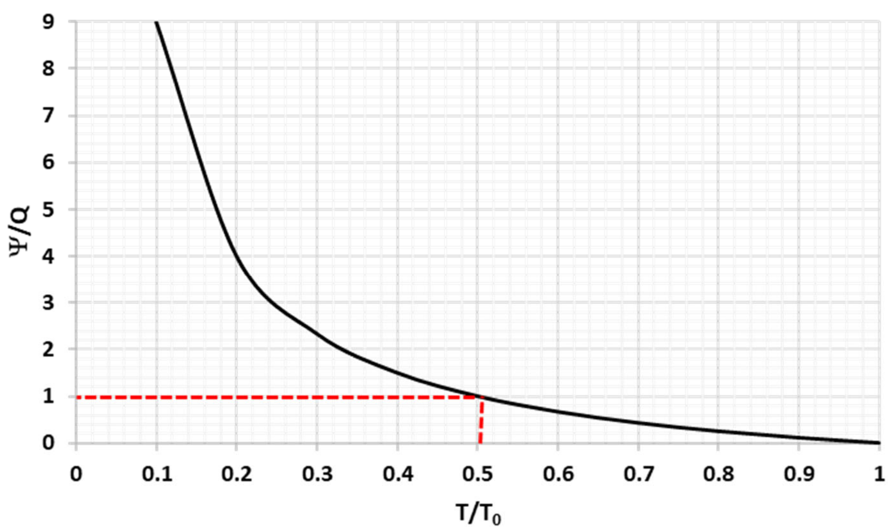

Figure 3: variation of the exergy factor with T/T_0.

Figure (4) illustrates the value of the exergy factor when temperatures are higher or lower than the reference temperature (atmospheric temperature). As can be seen, the exergy factor increases faster in the cold region than in the hot region as we move away from the reference temperature (25 °C). It is revealed that, even though the departure from the reference temperature is the same for both sides, the cold exergy (left side) is greater than heat exergy (right side). Hence, cold exergy must be recognized and recovered.

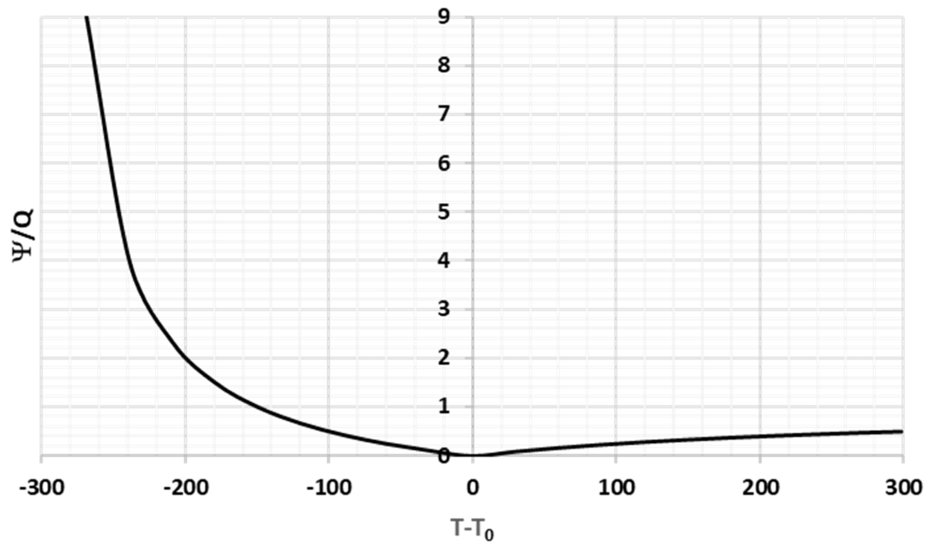

Figure 4: variation of the exergy factor with T-T_0.

The Thermodynamic Governing Equations for Open Systems [9]

For open system we may write:

The continuity equation:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{5}$$

First law equation:

$$\sum \dot{Q} + \sum \dot{m}_i\, h_i = \sum \dot{m}_e\, h_e + \sum \dot{W} \tag{6}$$

The first law of efficiency can be written as:

$$\eta^{1st} = \frac{Energy\ (sought)}{Energy\ (cost)} \tag{7}$$

where energy (sought) indicates the desired energy of the product leaving the system, and energy (cost) indicates the input energy of the system.

Exergy balance equation can be written as:

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_K - \dot{W} + \sum_{in} \dot{m}\psi - \sum_{out} \dot{m}\psi - \dot{\Psi}_D = 0 \tag{8}$$

The second law of efficiency (effectiveness or exergetic efficiency) is written as:

$$\varepsilon = \frac{Exergy\ (sought)}{Exergy\ (cost)} \tag{9}$$

where exergy (sought) indicates the desired exergy of the product, and exergy (cost) indicates the input exergy. The exergy flow is written as:

$$\psi = \psi_{ph} + \psi_{ch} + \psi_{ke} + \psi_{pe} \tag{10}$$

The quantity (ψ) is known as the stream or exergy flow associated with the restricted dead state. The change in kinetic and potential exergy terms are neglected, while chemical exergy is usually so minor compared with physical exergy and does not change in processes with constant chemical composition. In our case, the chemical composition of the natural gas does not change during the re-gasification process. The physical exergy is written as.:

$$\psi_{ph} = (h - h_0) - T_0(s - s_0) \tag{11}$$

The exergy function is defined as:

$$\beta_{P,T} = h_{P,T} - T_0 s_{p,T} \tag{12}$$

and hence:

$$\psi_{ph} = \beta_{P,T} - \beta_{P_0,T_0} \tag{13}$$

then:

$$\psi_{ph} = (h_{P,T} - h_{P_0,T_0}) - T_0(s_{P,T} - s_{P_0,T_0}) \tag{14}$$

By neglecting the chemical exergy and the change in kinetic and potential exergies $(\psi = \psi_{ph})$, the exergy changes between two states (1 and 2), which is also known as reversible work is given by:

$$\Delta\psi = w_{rev} = \beta_2 - \beta_1 \tag{15}$$

which can be written as [9]:

$$\Delta\psi = w_{rev} = (h_2 - h_1) - T_0(s_2 - s_1) \tag{16}$$

The change in exergy flow rate can be written as:

$$\dot{W}_{rev} = \Delta\dot{\Psi} = \dot{\mathrm{m}}[(h_2 - h_1) - T_0(s_2 - s_1)] \tag{17}$$

Thermo-Mechanical Exergy

Physical exergy (also called thermo-mechanical exergy) can be divided into thermal exergy and mechanical exergy. The former is recognized when the system is not in thermal equilibrium with the surroundings ($T \neq T_0$), and the latter is recognized when the system is not in mechanical equilibrium with the surroundings ($P \neq P_0$).

Then the thermal exergy is given by [10]:

$$\psi_{th} = \beta_{P,T} - \beta_{P,T_0} \tag{18}$$

$$\psi_{th} = (h_{P,T} - h_{P,T_0}) - T_0(s_{P,T} - s_{P,T_0}) \tag{19}$$

and the mechanical exergy is given by [10]:

$$\psi_{mech} = \beta_{P,T_0} - \beta_{P_0,T_0} \tag{20}$$

$$\psi_{mech} = (h_{P,T_0} - h_{P_0,T_0}) - T_0(s_{P,T_0} - s_{P_0,T_0}) \tag{21}$$

The benefit of dividing the physical exergy into thermal and mechanical exergies is illustrated in Figures (5&6). Thermodynamic tables and software like Computer-Aided Thermodynamic Tables (CATT), Engineering Equation Solver (EES), and Aspen HYSYS can be used to generate the thermodynamic properties and hence evaluate the contribution of thermal and mechanical exergies to total exergy. For methane as a working fluid, as can be seen, for temperatures below the atmospheric temperature, the thermal exergy decreases as the state temperature moves toward the atmospheric temperature while keeping the pressure at atmospheric pressure. Additionally, mechanical exergy increases as the state pressure moves away from atmospheric pressure while keeping the temperature at atmospheric temperature.

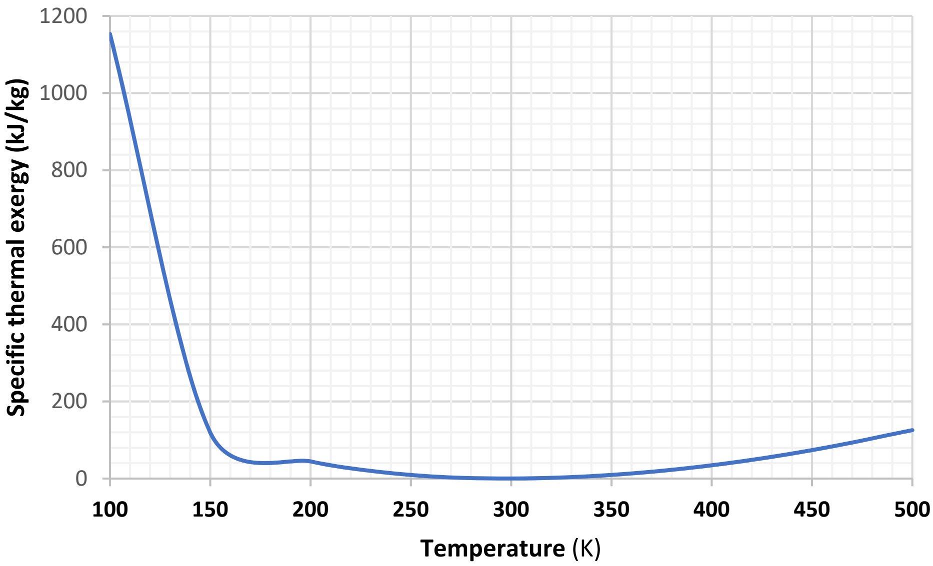

Figure 5: The variation of thermal exergy with temperature.

Thus, the physical exergy can be written as [11]:

$$\psi_{ph} = \psi_{th} + \psi_{mech} \tag{22}$$

Splitting the physical exergy into mechanical and thermal exergies enables us to select the appropriate method for recovering, either direct expansion to recover mechanical exergy or by exchange heat with surroundings atmosphere to recover thermal exergy.

The fuel exergy is calculated by [9]:

$$\dot{\Psi}_{fuel} = 1.065\dot{m}_{fuel}LHV \tag{23}$$

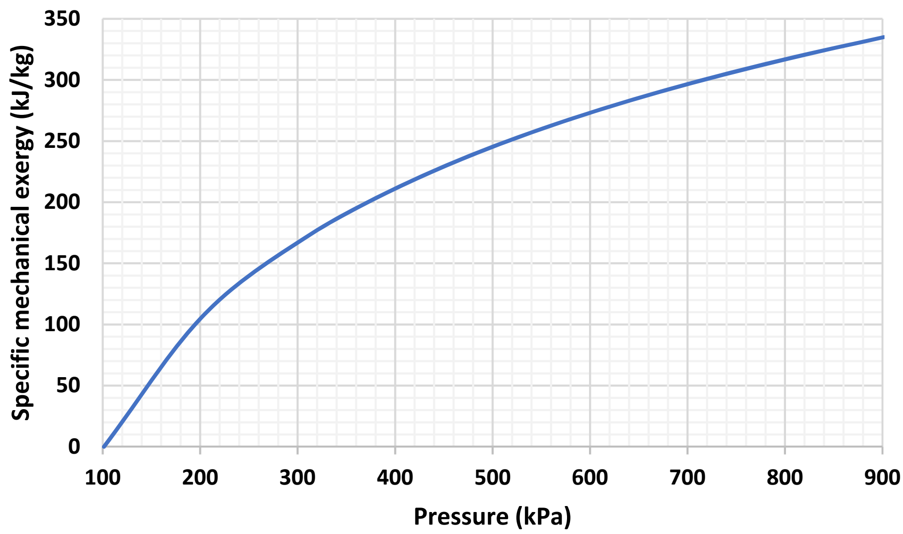

Figure 6: Variation of mechanical exergy with pressure.

Derna Steam Power Plant

Derna steam power plant has been selected to study the importance of recovering the cold exergy present in LNG and to anticipate the extent of the benefits we can derive from this energy source. Derna is a mountainous city in Libya located on the Mediterranean coast. The location coordinates are 32.5° latitude and 22.66° longitude. The station consists of high-pressure, medium-pressure, and low-pressure turbines; a condenser; two closed heaters for feedwater, one for high pressure and the other for low pressure; a deaerator; and two water pumps, one for the water exiting the condenser and the other for the water entering the boiler [12], as shown in Figure (7).

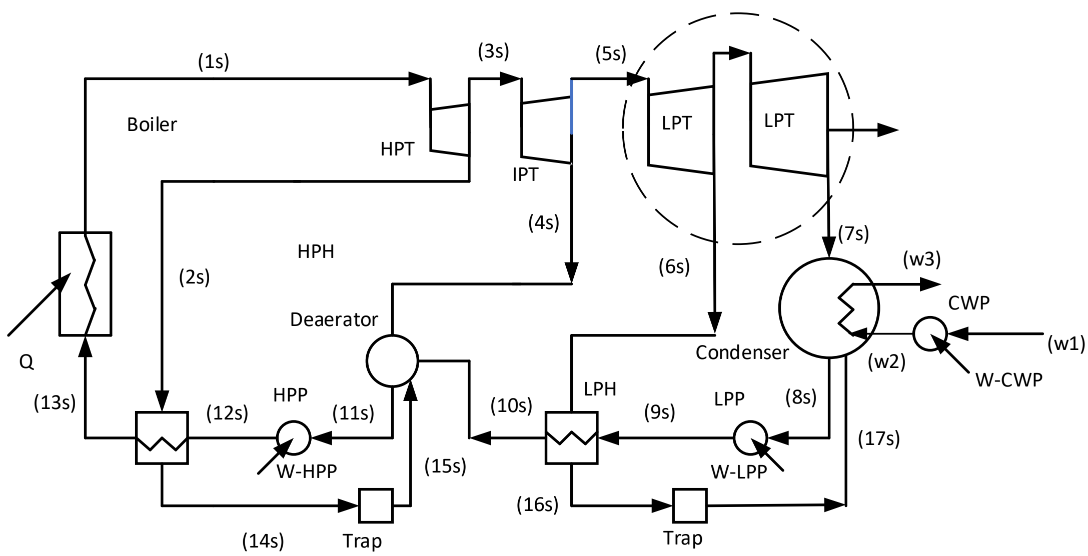

Figure 7: Schematic diagram of Derna power plant.

The input data for one unit of the Derna power plant is presented in Table (1). Steam exits the boiler at a temperature of 520 °C and a pressure of 8700 kPa. The extracted pressures are 2180 kPa, 602 kPa and 115 kPa, at the high-pressure heater, deaerator, and low-pressure heater, respectively. The condenser pressure is 6.2 kPa.

Table 1: Data for a Single Unit at the Derna steam station.

Item	Value	Item	Value
$\dot{m}_{fuel}$	4.5 kg/s	Turbine inlet temperature	520 ºC
LHV	43.4133 MJ/kg	Turbine inlet pressure	8700 kPa
$\dot{m}_{steam}$	67.48 kg/s	Stack gas temperature	130 ºC
Net power output	65 MW	$\dot{m}_{seawater}$	1662.8 kg/s
Boiler inlet temperature	216 ºC		

Direct Expansion Multi-Pressure LNG

LNG is turned back into gas at high pressures because of the needs of the natural gas supply system. There are differences in temperature and pressure compared to the surrounding environment. This difference is known as cold energy, which is produced when LNG changes from its very cold liquid state (-162 °C) to gas at normal temperatures (25 °C) [13]. Figure (8) presents three pressure levels cycle as given by [14]. In this cycle, as can be seen, the LNG is pumped by pump (1) and mixed with the outflow of the low-pressure turbine. The mixture at state 3 is pumped by pump (2) and mixed with a fraction of the outlet flow of the intermediate -pressure turbine. The mixture at state 5 is then pumped by pump (3) to state 6. The LNG at state (6) is evaporated in heat exchanger (1) by exchanging heat with the seawater before entering the high-pressure turbine at state 7. The natural gas is then expanded to state 8, and divided into two streams, stream 9 is heated by exchanging heat with the seawater in heat exchanger (3) to reach the desired state (state 10), at which the NG is utilized to power the steam turbine power plant. The other stream (state 11) enters the intermediate pressure turbine. The outlet of the intermediate pressure turbine (stream 12) is again divided into two streams, stream 13 toward the mixer (2), and stream (14) to exchange heat in heat exchanger with seawater (2). The outflow of the heat exchanger (2), state (15), enters the low-pressure turbine and leaves at state 16 to enter the mixer (1). The input data for this cycle is given in Table (2).

For analysis, LNG a pure methane (100% CH_4) and steady-state, steady-flow processes are assumed. Pressure drops due to friction, heat exchange with surroundings, and the change in kinetic and potential energies are neglected. Isentropic efficiency for the high, medium, and low-pressure turbines is 85%, 85% and 9%, respectively. Isentropic pumping processes are assumed for the three pumps.

Table 2: parameters of the working fluid in the direct expansion multi-pressure cycle.

Operating condition	Value
LNG temperature inlet	-161.6 ºC
LNG pressure inlet	1.013 bar
Three levels pressure in the cycle	4 bars, 35 bar, 150 bar
Temperature outlet three heaters	15 ºC

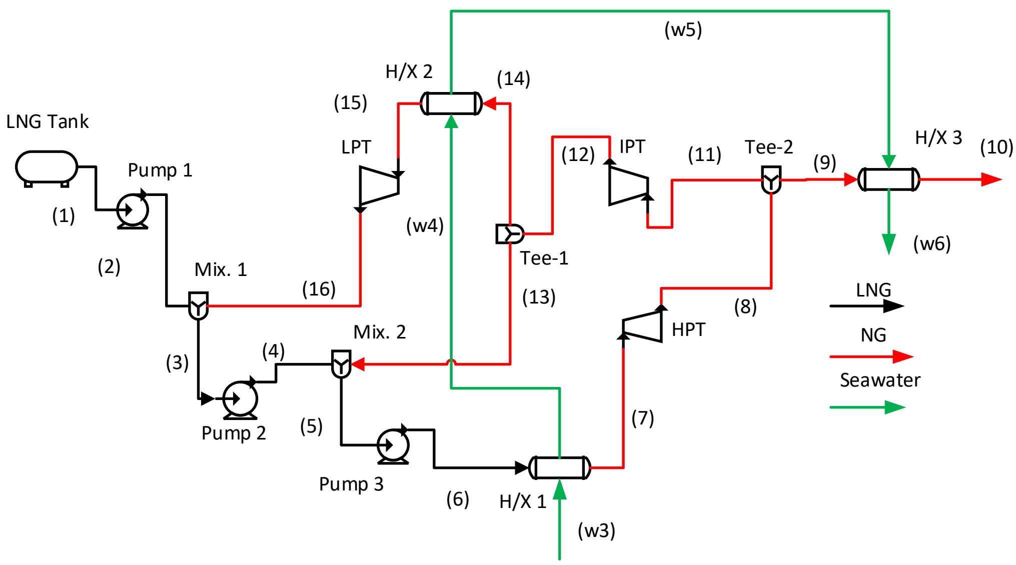

Figure 8: Schematic diagram for multi-pressure direct expansion processes.

The Hybrid Power Plant

Aiming to enhance the thermodynamic performance of Derna steam power plant, the regasification plant is integrated with the steam power plant as shown in Figure (9). The seawater that is leaving the condenser at state w3 with a relatively moderate temperature is utilized to evaporate the liquefied natural gas. Additional power is gained, and the overall thermodynamic performance will be enhanced.

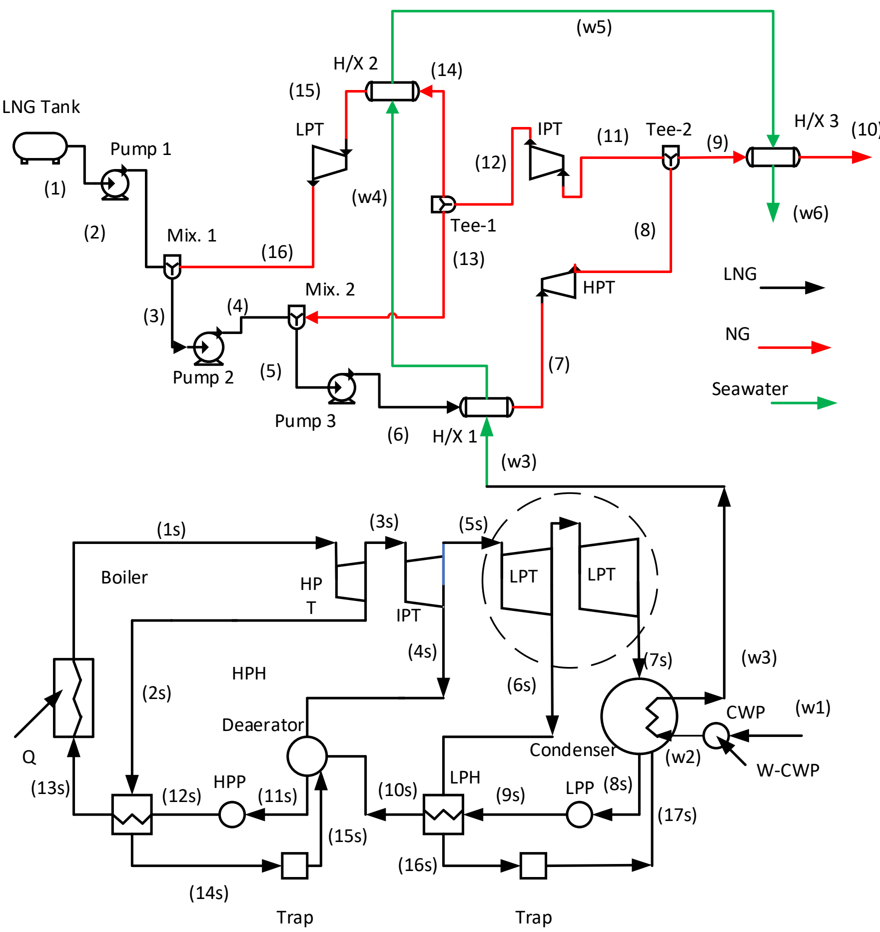

Figure 9: The hybrid power plant.

RESULTS

Derna Steam Power Plant

Derna steam power plant was selected as a case study to illustrate the approach of utilizing natural gas as fuel for power generation. The liquefied natural gas is shipped and then re-gasified using cooling water from the condenser. Table (3) presents the properties and exergy at various states of the plant. The cooling water, discharged from the condenser (state w3) at a flow rate of 1662.8 kg/s, a temperature of 29.48°C, and a pressure of 150 kPa, is used to evaporate the liquefied natural gas.

The heat supplied to the steam power plant is 195.36 MW [12]. The heat losses from the condenser, boiler, and the net power output are illustrated in Figure (10). A significant amount of heat is found to be rejected by the condenser into the atmosphere, which could potentially be utilized for re-gasifying liquefied natural gas (LNG)

Table 3: The properties and exergy at various states of Derna steam power plant.

State	T (°C)	P (kPa)	$\dot{m}\ (\frac{kg}{s})$	h (kJ/kg)	s (kJ/kg.K)	$\psi\ \left(\frac{kJ}{kg}\right)$	$\dot{\Psi}$ (MW)
1s	520	8700	68	-12485	6.74402	1434.44	97.5423
2s	330	2180	10.54	-12824	6.86129	1060.16	11.1741
3s	330	2180	57.46	-12824	6.86129	1060.16	60.917
4s	184.69	602	2.873	-13091	6.93308	772.259	2.2187
5s	184.69	602	54.587	-13091	6.93308	772.259	42.1553
6s	103.54	115	7.63672	-13352	7.02745	483.399	3.69158
7s	37.01	6.2	46.9503	-13640	7.40732	81.901	3.84527
8s	37.01	6.2	54.587	-15772	0.5291	0.85261	0.04654
9s	37.05	602	54.587	-15771	0.52944	1.45646	0.0795
10s	103.34	602	54.587	-15492	1.34492	37.4023	2.04168
11s	159	602	68	-15254	1.93266	99.5054	6.76637
12s	160.21	8700	68	-15244	1.93634	108.904	7.40547
13s	216.1	8700	68	-14966	2.53405	208.253	14.1612
14s	217.285	2180	10.54	-14615	3.26728	341.006	3.5942
15s	159	602	10.54	-14615	3.41242	297.732	3.13809
16s	103.54	115	7.63672	-15346	1.73215	67.3189	0.5141
17s	37.01	6.2	7.63672	-15346	1.90087	17.0166	0.12995
w1	15	101.3	1662.8	-15863	0.2244	0.7165	1.1914
w2	15.01	175	1662.8	-15863	0.2244	0.7911	1.3154
w3	29.48	150	1662.8	-15800	0.4348	0.2181	0.3627

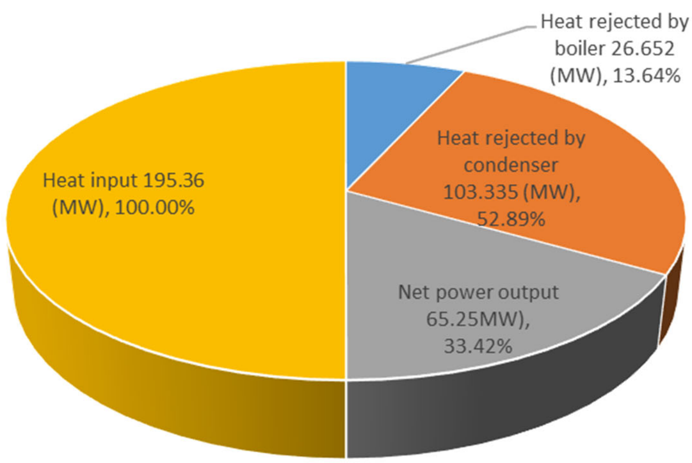

Figure 10: Details of the energy balance.

The obtained heat loss percentage is compared with the findings of [12] showing good agreement, as illustrated in Figure (11). The net power output is found to be equal to 65.25MW, consequently the thermal efficiency is 33.40% compared to 33.0% as given by [12].

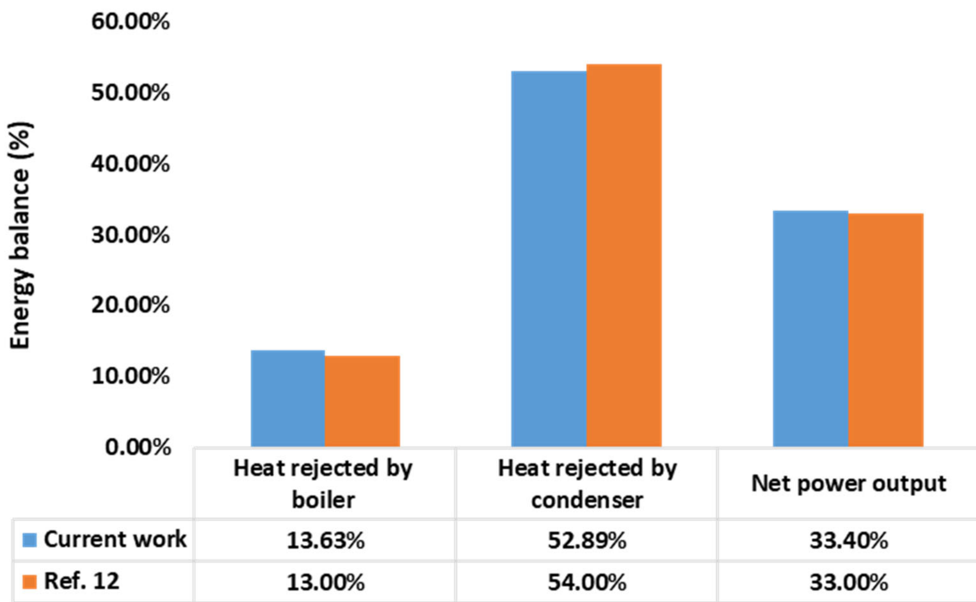

Figure 11: Energy balance [%], in comparison to that reported by [12].

Using Equation (23), the fuel's chemical exergy is 207.87 MW; consequently, the exergetic efficiency is 31.41%, compared to the 30.92% reported by [12]. Table (4) presents the exergy destruction of the plant's components, their contribution to fuel exergy and the exergetic efficiency. As expected, the highest exergy destruction occurs in the boiler, accounting for 59.90% of the fuel exergy.

Table 4: Exergy destruction in the power plant components.

Component	Exergy destruction (MW)	Exergy destruction (%)	Exergetic efficiency
Boiler	124.5158	59.9008	45.9483
Turbine	10.4606	5.0323	85.1977
Condenser	4.8977	2.3561	7.3289
Deaerator	0.5898	0.2837	92.0178
HPH	0.7971	0.3834	89.4889
LPH	1.2131	0.5836	61.7426
CP	0.0055	0.0027	89.8629
FP	0.0746	0.0359	89.0281
CWP	0.0228	0.0110	84.4642
Total	142.5769		

The results are compared with the findings of [12], demonstrating good agreement as shown in Figure (12).

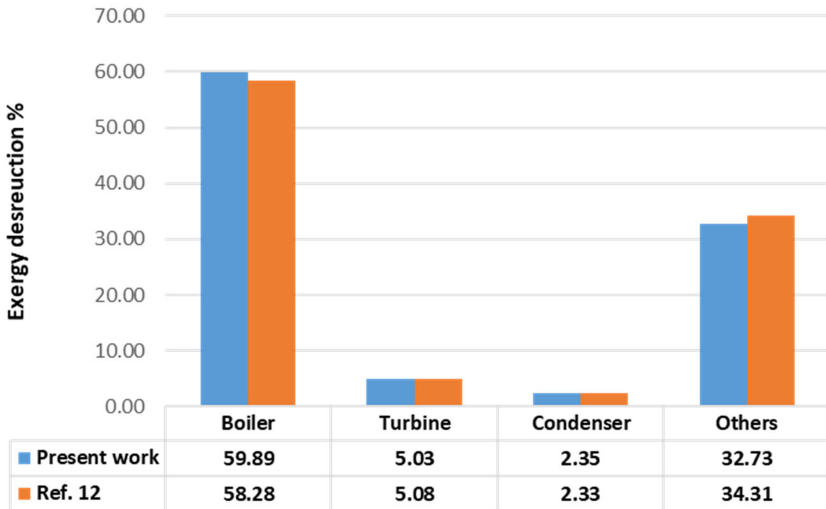

Figure 12: Exergy destruction [%], in comparison to that reported by [12].

The Gasification Plant

The re-gasification multi-pressure cycle, which is proposed to be integrated with the Darna power plant, is shown in Figure (8). The obtained thermodynamic properties and the calculated exergy are presented in Table (5).

Table 5: The properties and exergy at various states of the re-gasification cycle.

State	T(°C)	P(kPa)	$\dot{m}(\frac{kg}{s})$	h (kJ/kg)	s (kJ/kg.K)	ψ (kJ /kg)	$\dot{\Psi}$ (MW)
1	-161.60	101.30	106.10	-5579.08	4.76	1080.91	114.68
2	-161.50	400.00	106.10	-5578.37	4.76	1081.40	114.74
3	-141.89	400.00	119.15	-5507.96	5.34	978.76	116.62
4	-140.49	3300.00	119.15	-5500.58	5.35	984.30	117.28
5	-94.28	3300.00	201.48	-5284.15	6.73	790.28	159.23
6	-75.32	15000.00	201.48	-5242.77	6.74	827.68	166.76
7	15.00	15000.00	201.48	-4858.06	8.35	730.79	147.24
8	-65.32	4000.00	201.48	-4958.82	8.44	604.20	121.73
9	-65.32	4000.00	106.10	-4958.82	8.44	604.20	64.11
10	15.00	4000.00	106.10	-4739.19	9.34	555.57	58.95
11	-65.32	4000.00	95.38	-4958.82	8.44	604.20	57.63
12	-75.97	3300.00	95.38	-4970.95	8.45	588.83	56.16
13	-75.97	3300.00	82.33	-4970.95	8.45	588.83	48.48
14	-75.97	3300.00	13.05	-4970.95	8.45	588.83	7.68
15	15.00	3300.00	13.05	-4730.69	9.46	528.07	6.89
16	-95.39	400.00	13.05	-4935.45	9.59	283.97	3.71
w3	29.48	150.00	1662.80	-15868.45	3.05	0.20	0.33
w4	18.67	150.00	1662.80	-15915.07	2.89	0.35	0.59
w5	18.24	150.00	1662.80	-15916.95	2.88	0.40	0.66
w6	14.99	150.00	1662.80	-15930.97	2.83	0.80	1.33

The physical exergy of the main components is split into thermal and mechanical exergies and presented in Table (6). The main objective of the splitting is to highlight the fact that thermal exergy decreases with increased temperature for states at temperatures lower than the reference temperature. For instance, the inlet thermal exergy of the working fluid for heat exchanger 1 is 19.77 MW and is reduced to 0.25 MW as its temperature increases due to positive heat transfer from the seawater, which is at a higher temperature. As can be seen, the mechanical exergy is kept constant at 146.99 MW since the pressure loss is neglected across the heat exchanger. Because of the heating process, the physical (total) exergy decreases from 166.76 MW to 147.24 MW. The same results apply for heat exchangers 2 and 3.

For the turbines, the thermal increases and the mechanical exergy decreases as the temperatures and pressures decrease during the expansion process. For instance, for high pressure turbine the thermal exergy increases from 0.25 MW to 9.99 MW, while the mechanical exergy decreases from 146.99 MW to 111.75 MW. Because of the expansion process, the physical (total) exergy decreases from 147.11 MW to 121.63 MW.

The exergy balance for the proposed gasification cycle is shown in Figure (13). It was found that the exergy destruction is equal to 39.91 MW. The net input exergy is 54.41 MW, and the exergetic efficiency is 27.27%.

Table 6: Splitting total exergy into thermal and mechanical exergies for the main components.

Component		$\dot{\Psi}_{th}$ (MW)	$\dot{\Psi}_{mech}$ (MW)	$\dot{\Psi}_{total}$ (MW)
H/X 1	In	19.77	146.99	166.76
	Out	0.25	146.99	147.24
H/X 2	In	0.80	6.88	7.68
	Out	0.01	6.88	6.89
H/X 3	In	5.26	58.85	64.11
	Out	0.10	58.85	58.95
HPT	In	0.25	146.99	147.11
	Out	9.98	111.75	121.63
IPT	In	4.73	52.90	57.63
	Out	5.88	50.28	56.16
LPT	In	0.01	6.88	6.89
	Out	0.95	2.75	3.71

Details of exergy destruction are presented in Table (7). The greatest exergy destruction is found in the heat exchanger (1); this is due to the large flow of LNG through it. The percentage of the exergy destruction based on the total input exergy, is also presented in Table (7).

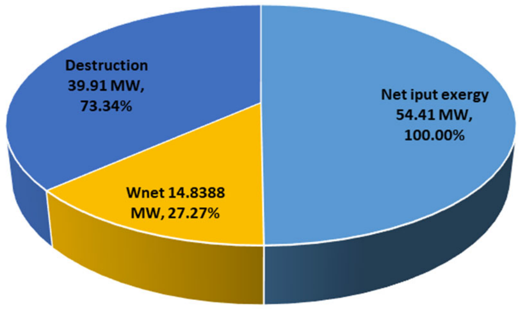

Figure 13: Exergy balance for the multi-pressure Cycle of LNG.

Table 7: Details of exergy destruction.

Component	Exergy destruction (MW)	Exergy destruction (%)
Pump1	0.0234	0.04
Pump2	0.2201	0.40
Pump 3	0.8023	1.47
Sub-total	1.0458	1.92
HPT	5.2043	9.57
IPT	0.3091	0.57
LPT	0.5133	0.94
Sub-total	6.0268	11.09
MIX1	1.8237	3.35
MIX2	6.5304	12.00
Sub-total	8.3542	15.35
HX1	19.2687	35.41
HX2	0.7218	1.33
HX3	4.4880	8.25
Sub-total	24.4784	44.99
Total	39.9052	73.34

The Hybrid Power Plant

The goal is to improve the thermodynamic performance of Derna power plant by integrating it with the gasification system. This connection will use the waste heat from the steam that leaves the steam turbine to turn liquefied natural gas back into gas, as shown in Figure (9). The consumption rate of the NG is 106.1 kg/s, that is 3.34 million tons annually.

The benefits of integrating the two cycles are presented in Table (8). As can be seen, linking the steam power plant with the re-gasification cycle increases the net power output from 65.28 MW to 80.12 MW. Both cycles are powered by the same amount of fuel; that is, the energy and consequently the exergy costs are the same for both cycles. As a result, the net power output, first law efficiency, and exergetic efficiency increase by the same percentage, which is 22.73%.

Table 8: The results of linking the re-gasification cycle with Derna power plant.

Item	Derna	Hybrid cycle	Increase (%)
Net power output (MW)	65.28	80.12	22.730
First law efficiency (%)	33.42	41.01	22.730
Exergetic efficiency (%)	31.41	38.54	22.730

Seeking an improvement in the thermodynamic performance, the natural gas at state 7 is manipulated between 10 and 22 °C as shown in Figure (14). Beyond 22 °C, a trace of vapor at pump 3 inlet is observed. The results indicate that there is no significant improvement by raising the temperature of state 7, since the net power increases to 80.76 MW, the first law efficiency to 41.34%, and the second law efficiency to 38.85%.

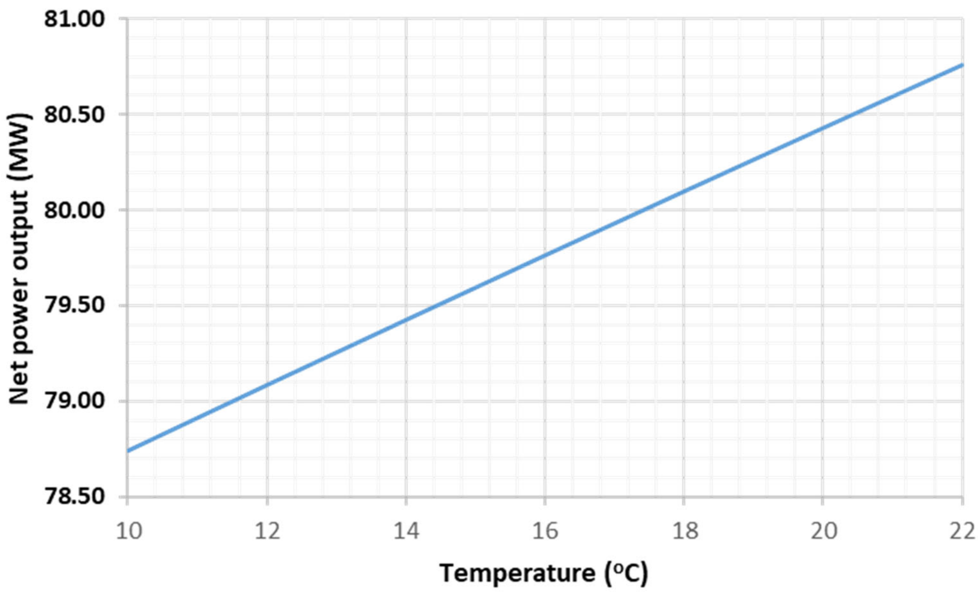

Figure14: The effect of changing the gas inlet temperature on turbines.

LNG mass flow rate is another parameter that might affect the thermodynamic performance of the hybrid cycle. The impact of varying the LNG flow rate on the net power output, first law efficiency, and the exergetic efficiency is tested. The mass flow rate varies between 50 and 150 kg/s. The results are shown in Figures (15&16). As can be seen, there is a significant improvement in thermodynamic performance as the LNG flow rate increases; however, the rate of LNG flow depends on its availability at the site of the plant.

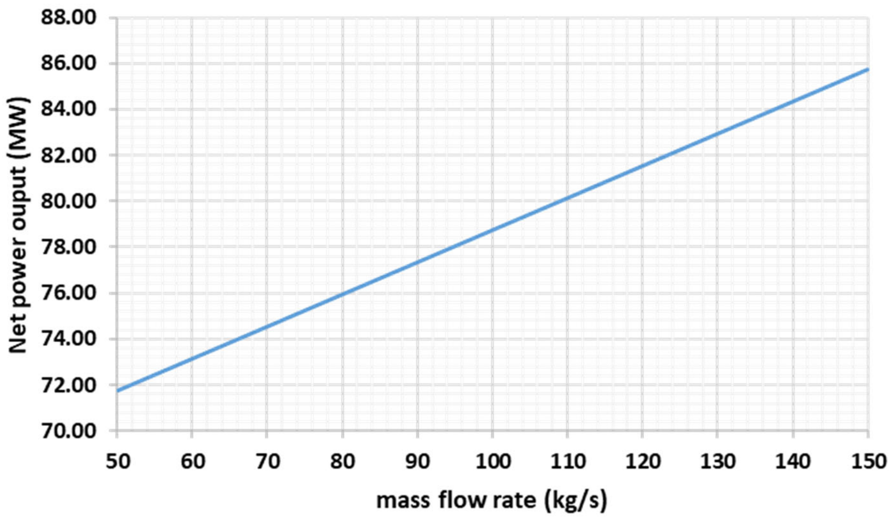

Figure 15: The impact of LNG flow in the hybrid cycle plant on net power output.

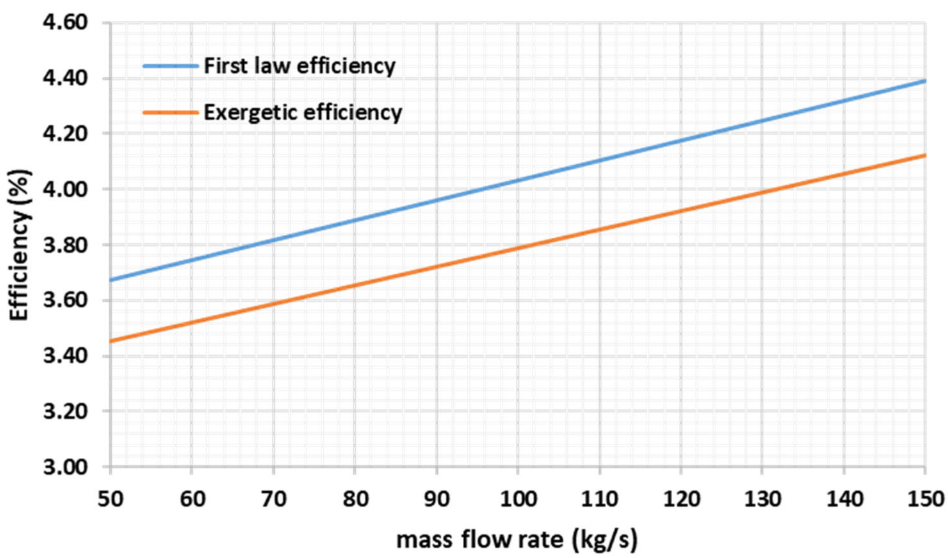

Figure 16: The impact of LNG flow in the hybrid cycle plant on first and exergetic efficiencies.

CONCLUSIONS

The following conclusions are drawn from this work.

1) This study presents the concept of cold exergy. It shows how energy and exergy flow when temperatures are above or below a reference temperature (T_0).
2) Cold objects take in energy from the environment and release exergy, which is called cold exergy.
3) The study highlighted that if the system's temperature is lower than half of reference temperature, the flow of cold exergy is greater than the flow of heat. This emphasizes the need to recover cold exergy from low-temperature systems.
4) A thorough analysis was done on turning liquefied natural gas back into natural gas, revealing that 1080.91 kJ/kg of liquefied natural gas can be converted into usable energy.

5) Since the heat emitted from the Derna station through the condenser is constant and determined by the plant itself, and the gas exit temperature from the condenser is specified by the design, the electrical power output of the natural gas turbines is affected by the mass flow rate of the liquefied natural gas.
6) The total power output of the proposed hybrid cycle increased by 22.73% over that of the conventional cycle.
7) Assuming the use of proposed power generation stations in Derna, the consumption is estimated at 3.34 million tons annually of liquefied natural gas, which is supplied in the form of natural gas to the pipeline.

NOMENCLATURE

Symbols		h	first law efficiency
f	factor	e	exergetic efficiency
H (kJ/kg)	enthalpy	β	exergy function
H/X	heat exchanger	**Subscripts**	
HPT	high pressure turbine	0	ambient
IPT	intermediate pressure turbine	1,2,3, …	states
LHV (MJ/kg)	lower heating value	C	cold
LNG	liquefied natural gas	ch	chemical
LPT	low pressure turbine	D	destruction
$\dot{m}$ (kg/s)	mas flow rate	e	exit
NG	natural gas	ex	exergy
P (kPa)	pressure	H	hot
Q (MJ)	heat flow rate	i	inlet
s (kJ/kg.K)	entropy	k	component
T (^{o}C)	temperature	ke	kinetic exergy
w (kJ/kg)	specific work	mech	mechanical
$\dot{W}$(MW)	power	pe	potential exergy
Greek letters		ph	physical
$\psi \left(\frac{kJ}{kg}\right)$	specific exergy	rev	reversible
$\dot{\Psi}$ (MW)	exergy rate	s	steam cycle
Δ	change	th	thermal

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