LNG Regasification System to Enhance the Performance of Gas Turbines and Water Desalination Systems

Asad A. Salem and Emad Hudiab

Abstract- The objective of this research is to propose a new approach in regasification of Liquefied Natural Gas (LNG). In this approach a solar energy powered Liquefied Natural Gas (LNG) regasification system that incorporates a water desalination process utilizing the cold energy available in the LNG. The solar energy is utilized in an air humidification unit, were hot and saturated air is produced. The thermal energy contained in the saturated and hot air is employed by a LNG regasification unit which converts LNG to natural gas (NG). During the regasification process, the hot and saturated air is cooled below the Dew-point temperature producing a sizable amount of fresh water. The proposed system is tested under various conditions of temperatures and relative humidity. The results show that there is a substantial increase in the efficiency of the gas turbines (GT) which translated to the efficiency of the power plant as a result of cooling the air that is fed to the GT. in such approach the regasification heat requirement will be served through concentrating solar power system CSP, a regasification model of 1 Billion SCFD (19000 ton/day) is considered, the expected fresh water production for this proposed model is around 6.5 million liter per day, the produced cold dry air of this proposed regasification technique would enhance the power out-pout of the attached gas turbines. The proposed system is a mix of various technologies and a proposal for the better utilization of energy to generate power.

Keywords- Desalination, LNG, Regasification, Solar Energy

I. INTRODUCTION

One of the main concerns in the natural gas industry is the regasification of the LNG (Liquefied Natural Gas. The common techniques adapted by the industry have been a challenge to both power generation and receiving terminals of the LNG. LNG is a natural gas that has been cooled to a temperature of -161 ^{o}C where it turns to liquid. Liquefaction reduces the volume of the natural gas (NG) by 600 times which makes it more practical to be shipped and transported through specially designed vessels. The shipped gas is received via either onshore or offshore receiving terminals [2].

Onshore and offshore LNG receiving terminals have been built around the world responding to the increased demand on the imported LNG to these receiving terminals.

The global LNG demand has risen by an estimated 7.6% per year over the same period, almost three times faster (Figure 1).

Global gas demand is expected to continue to grow strongly. In its most recent annual World Energy Outlook, the International Energy Agency (IEA) forecast a growing role for natural gas in the world's energy mix, with the natural gas share growing from 21% in 2010 to 25% in 2035, with natural gas as the only fossil fuel whose share was growing.

Global LNG demand by 2030 could, however, be almost double that of the estimated 2012 level of about 250 million metric tonnes. Japan, South Korea and Taiwan (collectively, JKT) have been and are expected to remain the backbone of the global LNG market, while China and India are expected to be the biggest sources of additional LNG demand [1].

At those terminals the LNG vessels are connected to the receiving terminals as part of a complete chain of processes of handling the LNG to be vaporized into NG which is used to be conveyed through the NG pipelines to the final destination in the LNG regasification process can be conducted through adapting several types of vaporizers; each type of vaporizers has its own advantages and disadvantages.

The traditional type of vaporizers is the gas fired vaporizers, or what is commonly called submerged combustion vaporizers SCV (refer to figure 2), SCV is commonly used in US and it is industry proofed with efficient heat transfer, while its main disadvantages are the high operation cost, as 1.5 to 2 % of the vaporized LNG will be fired to serve the regasification process, and the SCV results in acid water that is required to be treated, moreover; the air emission is another environmental impact of SCV such as CO_2, CO, and NOx [6].

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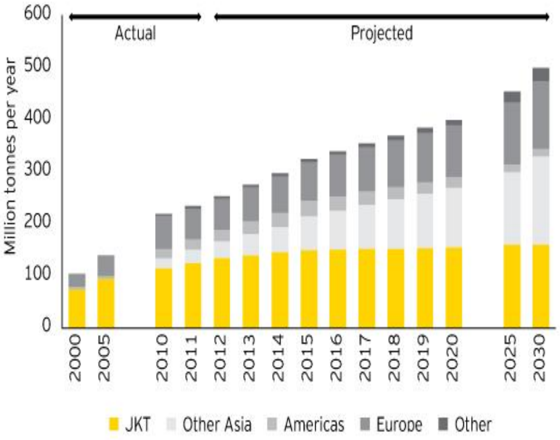

Figure 1: LNG Import Demand (US EIA) [1]

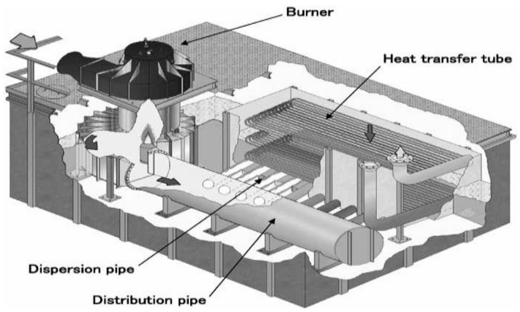

Figure 2: Schematic of SCV [6]

The other common technique in LNG vaporization is the falling film, open rack (ORV), sea-water vaporizers; in which the LNG is introduced through manifold to bank of vertical panels constructed of special extruded fins, on which the heat transfer between the sea water and the LNG is taking place and the natural gas will be collected through a manifold connected to the NG pipeline [3]. The main advantage of open rack type (ORV) is the low emissions and better economy compared to SCV, but it has restrictions and impact on the seawater quality, and using the seawater results in higher corrosion rate for the pipes and the heat exchangers that requires more frequent preventive maintenance and applying anti-corrosive measures, figure 3 illustrates the schematic of the ORV [7].

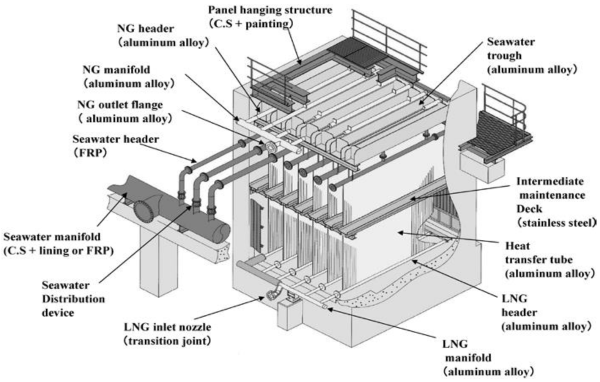

Figure 3: Schematics of ORV [7]

The recent trend in the LNG regasification is using the atmospheric heat exchangers as a competitive replacement for both SCV and ORV, but in general the LNG industry is very slow in accepting new technologies due to large investment cost and the risk implied in such change [5], in this regard Mustang Engineering LP developed a vaporizer using the atmospheric heat exchangers called SAV (Smart Air Vaporizer), in which the vaporizer relies on air instead of either gas or seawater, better process economy, higher versatility as it can be mounted onshore, offshore, or on board of LNG carriers (vessels), environmental friendly but requires supplemental heat source [4]. Figure 4 shows a schematics of the SAV provided by Mustang Engineering [6]

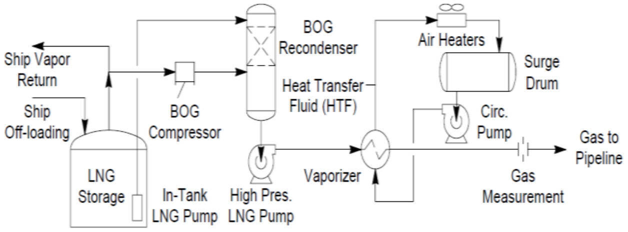

Figure 4: SAV provided by Mustang Engineering [6]

II. SYSTEM DESCRIPTION and METHODOLOGY

The objective of this proposed work is to develop a LNG re-gasification plant that is powered by a renewable energy source and to utilize the synergy of the LNG to enhance the efficiency of power generation systems and to couple the regasification plant with water desalination system. Concentrated solar energy will used to heat ambient air, this heated ambient air is, then, introduced to a humidification process. Though this humidification process the heated ambient air will reach saturation and will be exposed to LNG via a heat exchanger. During this exchange of energy the evaporation of the LNG will take place and the saturated hot air is cooled below the dew point were fresh water is produced as a result of this energy exchange. The evaporated NG will go through additional heating, and then introduced o gas turbines along with cold dry air for combustion. The introduction of dry cold air enhances the efficiency of the gas turbines. This new process produces fresh water, enhance the efficiencies of gas turbines and reduces the carbon foot print of such technologies. Hence, improving the economics of the LNG regasification systems and produce useful by- products that can be utilized to enhance the performance of power generation systems or in many other applications and subsequent downstream processes of the NG power stations.

The basic layout of the proposed LNG regasification system is divided into two main sub-cycles or systems as it is illustrated in figure 5; the LNG regasification sub-cycle and the air sub-cycle.

In the LNG sub-cycle, the LNG is pumped from the storage tank (or the vessel) to the regasification heat exchangers; in which the LNG will turn into NG and heated through the hot humid air blown through the air sub-cycle, the natural gas can be conveyed through the NG pipeline to the attached gas turbines in the power stations.

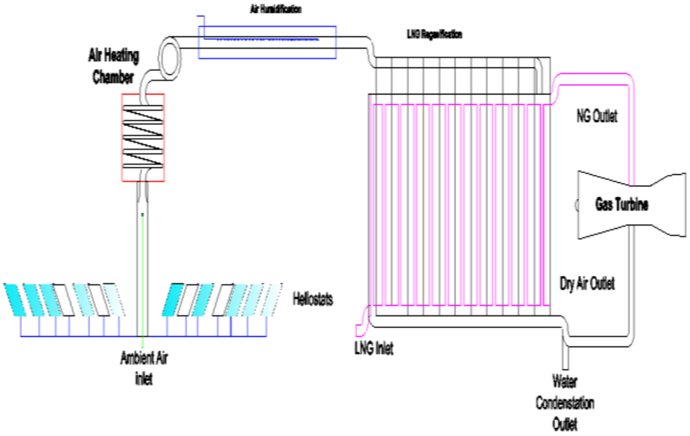

Figure 5: A Schematic of the Proposed LNG Regasification Plant

While on the air sub-cycle; the available humid air is being heated and humidified relying on the available solar energy collectors, the saturated humid air at high temperature is blown through the vaporization heat exchangers, which will transfer the heat toward the cold LNG sub-cycle, the outcome of air sub-cycle will be a cold dry air and cold water both at the temperature of outgoing NG of LNG sub-cycle.

III. PROPOSED REGASIFICATION PLANT

The solar irradiance is collected and concentrated through the heliostats (solar tracking mirrors), which is arranged in a clusters to focus the solar incident into the air heating chamber (receiver); which is filled up with a heating media (molten salt) that is including the submerged air heating pipeline; in which the ambient air is heated up and conveyed using a suction fan (attached to the gas turbines) toward the humidification unit, in this unit the sea water is misted and introduced to the hot air pathway which leaves the humidifier saturated at 85 ºC, this saturated hot humid air is acting as the heating source in the regasification heat exchangers that are designed to accommodate a counter flow for the sub-cooled LNG and the heating air, the process takes place on a massive heat transfer area which requires a smarter design for the flow and the heat exchanger geometry to come up with an efficient feasible regasification process.

The outgoing NG and the dry cold air would operate the connected gas turbines in the attached power generation stations, while the cold water which is the third by-product of this regasification process is potable fresh water that can be utilized in cooling applications as well.

The plant is designed based on the coldest climate along the year (the biggest estimated solar mirrors field) so the production will exceed the expected send-out rate during the summer and maintain the design send-out rates during the cold winter. Production fluctuation can be managed through an optimum plant operation scheme, in which the annual shutdown and periodic maintenance will be scheduled during the low production season (cloudy winter), and that would give a better chance for more focus on production during the peak summer season (higher demand on electricity, and air conditioning). The additional solar energy collected through the oversized solar field can be stored in terms of molten salt in a form of latent heat required for phase change (melting the salt), and that can accommodate the energy requirement for overnight operation.

IV. BASIC CONSIDERATIONS

A. The LNG send-out rate is 28 MCMD.

B. The LNG regasification is assumed to run under constant one atmospheric pressure for simplicity, the LNG is assumed to consist solely of methane, and the regasification process is assumed to take place under constant pressure (1 atm).

C. All the air, solar, and climate specific data have been adapted for Houston, Texas as the location in which the model is to be operated.

V. THE LNG –NG SUB-CYCLE

The LNG is pumped from the source toward the regasification heat exchangers, in which the LNG is heated from (T_1 = -182 ºC) to the boiling point (T_b = -162 ºC), on which the boiling process would take, then the gas is heated up to ($T_2 = 5$). The heating requirement for such process is served through the hot humid air provided by the air-solar sub-cycle, for the sake of simplicity; the targeted send-out rate of the gas has been converted into mass flow which is equal to 221.3 Kg/s, and the total heating requirement is calculated based on the enthalpies of the LNG and NG in equation (1) and found around 208 MW.

$$Q_{LNG\ vap} = m'_{LNG}(\,h_2 - h_1) \qquad (1)$$

Where:

$Q_{LNG\ vap}$: LNG required thermal power KW.
m'_{LNG} : LNG send-out mass flow rate Kg/s.
h_2 : NG Specific Enthalpy ($T_2 = 5^o\ C$) KJ/Kg.
h_1 : NG Specific Enthalpy ($T_1 = -182^o\ C$) KJ/Kg.

$$m'_{Humid\ Air} = Q_{LNG\ vap} / \Delta h_{Humid\ Air} \qquad (2)$$

Where:

$m'_{Humid\ Air}$: Required saturated humid air mass-flow rate required for vaporization process in Kg/S.

$Q_{LNG\ vap}$: LNG Regasification required Thermal Power KW.

$$\Delta h_{Humid\ Air} = C_{p\ da}\,\Delta T_a + X_s (C_{pw}\,\Delta T_a + h_{we}) \quad (2.1)$$

Where:

$\Delta h_{Humid\ Air}$: Specific enthalpy change in humid water to reach saturation over the ΔT_a .

$C_{p\ da}$: Specific heat of dry air KJ/Kg. ^oK.

ΔT_a : Change of air temperature during the LNG vaporization process ^oC.

X_s : Absolute humidity at saturation level Kg_{Vap}/Kg_{air}

$C_{p\ w}$: Specific heat of water vapor in KJ/Kg. ^oK.

h_{we} : Latent heat of vaporization of water which is assumed here 2504 KJ/Kg

Though and optimization process and based on equations (1) and (2), the required air mass-flow rate of the targeted saturated humid air (T = 85 ^{o}C) is 90 Kg/s is required in this process; and 76 kg/s of water can be extracted from a total flow of saturated humid air of about 90 Kg/s.

It has been a challenge to accurately estimate the enthalpy of the ambient air along the year in Houston. We have employed an extended experimental data and equation (2) with slight modification, as X_s has been located for each average monthly temperature from the humid air table in chapter 6 of reference [14], then calculating the ($X_{ambient\ air} = RH\% \times X_s$) and plug it in the equation above to find the enthalpy of ambient air (h_i) as per table 1.

Table 1: Estimated air mass-flow rate, humid air heating requirements, and solar collectors estimated area

Month	h_w (KJ/Kg)	h_a (KJ/Kg)	X_s (Kg/Kg)	h_i (KJ/Kg)	Power (MW)	Collector (Km^2)
Feb	35.3	12.6	0.0094	12.85	206.9	1.50
April	58.7	20.2	0.0514	20.86	206.1	1.34
June	84.64	27.0	0.0226	28.49	205.5	1.17
Aug	89.49	28.1	0.0241	29.72	205.3	1.15
Oct	61.42	20.2	0.0160	20.91	206.1	1.15
Dec	34.05	11.8	0.0088	12.03	207.0	1.99

VI. AIR FLOW FAN REQUIRED POWER

Fan selection starts with a basic knowledge of system operating conditions: air properties (moisture content, temperature, density, contaminant level, etc.), airflow rate, pressure, and system layout. This condition determines which type of fan—centrifugal or axial—is required to meet service needs [15].

The air flow rate required for the regasification process effect the energy consumption of this proposed system, the mass flow rate estimated for the targeted regasification rate is around 90 kg/s, the power consumed by the fan to deliver such mass flow rate can be briefly estimated using the following equation:

$$P_{Air\ fan} = (P_t \times V'_{air}) \Big/ (\mu_f \times \mu_b \times \mu_m) \qquad (3)$$

Where:

$P_{Air\ fan}$: Power required by fan (W).

P_t : Total pressure (Pa)

V'_{air} : Humid air volumetric flow-rate (m^3/s).

μ_f : Fan efficiency (%).

μ_b : Belt efficiency (%).

μ_m : Motor efficiency (%).

In a counter-flow heat exchanger in which the LNG is being heated through the counter-flow of the humid air blown around the heat exchange surfaces, and assuming full flow condition and overall heat transfer coefficient of is estimated to be around 21 (W/ m^2.K) under atmospheric pressure; the estimated required area for vaporization and heating of LNG (refer to equation 4) is about 75000 m^2 (using the logarithmic mean temperature difference - LMTD [12]; which indicates a sizable heat exchanger (10 x 6x 6 meter plate heat exchanger) is required for such process. The ambient air (which varies along the year) of the selected site (Houston is adapted here) is pumped through the heat exchanger in which the molten salt heats up the air up to 85 ^{o}C passing through the attached humidifier to reach the saturation state, before being pumped through the regasification heat exchanger of the LNG-NG sub-cycle, the heat requirement for the air to reach the targeted temperature and humidity is served through the proposed solar system which varies according to the average monthly temperature and humidity, the required average heating requirement is calculated using equation (2), in which the heating requirement is calculated as the difference in the enthalpies of both humid air (at the ambient average monthly temperature) and the enthalpy of saturated air at 85 ^{o}C.

The required area of the solar collectors will vary according to the monthly fluctuation in the temperature and humidity of the ambient air in Houston along the year, table 4 summarizes the heating requirement and the area of the solar collectors to serve the air heating (required for regasification process) in each month along the year in Houston based on equation 4.

$$A_{solar} = Q_{LNG\ vap} \Big/ Q_{solar\ Irradince} \qquad (4)$$

Where:

A_{solar} : Required area of solar collecting mirrors to produce $Q_{LNG\ vap}$ in m^2.

$Q_{solar\ Irrad.}$: Average sun irradiance power KW/m^2, (estimated based on reported irradiance) [10].

The heating requirements for the regasification is served through the solar collecting mirrors (Heliostats) concentrating the solar irradiance into the heating chamber in which the heating media will be utilized to heat up the air being pumped through, and then through the humidifiers where a sea water will be misted in the air pathway to reach the saturation at 85 ºC, which in turn is utilized in LNG regasification heat exchangers.

The heating chamber includes the air heating pipeline which is submerged in the molten salt which acts as the heating and thermal storage media as per the schematic shown in figure 6.

The molten salt used in CSP (concentrating solar power) proved to be a sufficient heating media that may reach up to 565 ºC, and may store the heat after sunset up to 6 hours (the molten salt consists of 60% Sodium Nitrate and 40% Potassium Nitrate), the primary advantages of molten nitrate salt as the heat transfer fluid for a solar power tower plant include a lower operating pressure and better heat transfer properties. This translates into a smaller, more efficient, and lower cost receiver and support tower [22].

The hot humid air (which is acting as the heating media to vaporize the LNG) can be further heated. But, it has been noticed that higher temperatures would result in higher moisture content capabilities under saturation condition. That results also in lower requirements for air mass-flow and higher heating energy requirements to accommodate high latent heat of water vaporization, so among other scenarios of humid air temperatures in the range of 85-90 ºC would form the optimum operation temperature as it can be noticed in figure 7.

While the increase in temperature results in raising the required heating energy; the expected condensate flow rate will not be improved in the same manner, notice the major increase in heating demand versus the minor increase in water condensation rate as we increase the operating temperature.

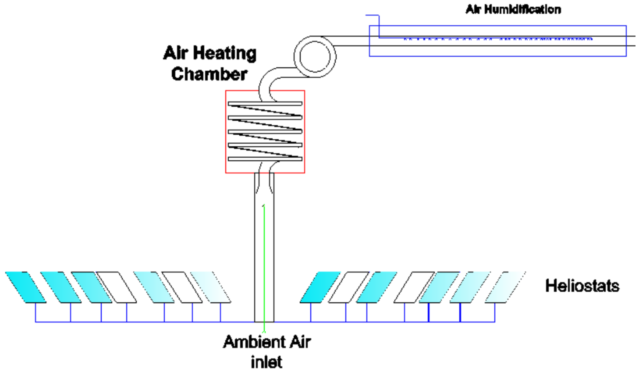

Figure – 6: Heating and humidifying air using CSP Tower.

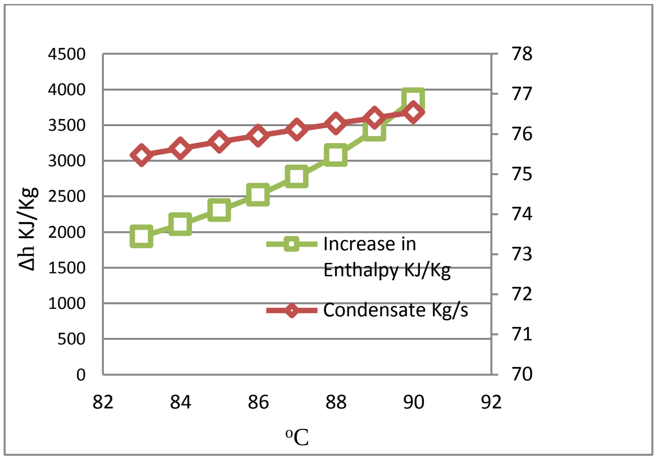

Figure 7: Effect of increasing temperature on the increase of specific enthalpy required for regasification and the expected increase in condensate flow.

Table 2: The expected Increase in Condensation and heating requirements on various operation temperatures

Operation Temperature ºC	Condensate expected Rate Kg/S	Increase in Enthalpy (KJ/KG)
83	75.47	1937.87
84	75.64	2107.22
85	75.81	2304.99
86	75.96	2521.11
87	76.11	2776.83
88	76.26	3076.89
89	76.41	3432.21
90	76.55	3859.84

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VII. THE ENHANCEMENT EFFECT ON GAS TURBINE PERFORMANCE

In addition to the fresh water the proposed system will result in a sensible flow rate of cold dry dense air, which can be connected to the attached gas turbine air-intake.

The effect of air-intake temperature and humidity is affecting the performance of the gas turbine is profound. Indeed, a 1oC reduction in air in-take temperature can increase the gas turbine output by up to 0.5%. As the air is cooled and the humidity is reduced the performance of the gas turbine is improved proportionally [16], figures 8 and 9 shows the trend of the turbine performance versus the air temperature and humidity respectively. In figure 9 it is noticeable that the output line is improved as we reduce the temperature, so if we consider the ambient condition in Houston on November is 16 ºC, so using the 5 ºC by-product cold air of the proposed regasification system would improve the output power with almost 5%, and by about 15-25% during summer while the absolute dry air would be more dense and as per figure 9; the power output would be improved as well.

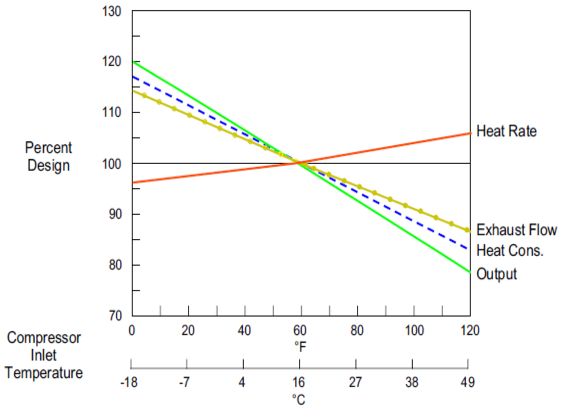

Figure 8: Effect of intake air temperature on Gas Turbine (GE MS7001) Output [17]

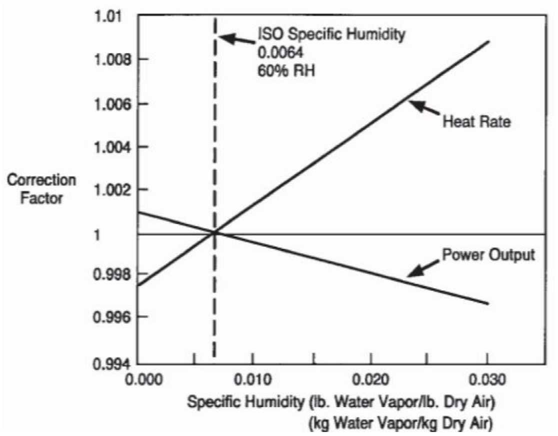

Figure 9: Effect of intake air humidity on Gas Turbine Output [17]

The proposed model is powered by solar energy collected by concentrating mirrors which reflect high intensity solar energy into a heating chamber in which the heat is stored in form of molten salt that is used to heat up and humidify the ambient air to the targeted temperature and humidity. Table 2 summarizes the average values of the proposed model parameters.

The proposed regasification plant is designed on the least solar heating capabilities of December in Houston, which requires around 2 Km^2solar collection areas, of course this will not eliminate the fluctuation in regasification send-out rate along the year, but that can be optimized through adapting smart operation schemes in which the annual shutdown of the plant will be conducted in the least production month, while the shortage of production will be compensated within the expected excess production during the peak production season in summer.

Table 3: The Proposed Model Annual Average Parameters

LNG out Rate *MCMD*	LNG out Rate *Kg/S*	Humid Hot air mass flow *Kg/S*	Condensate flow rate *Kg/S*	Dry Air flow rate *Kg/S*
28	221.3	90.25	75.81	14.44
Avg. required Solar Power (MW)	Avg. Solar Collection Area (Km^2)	Avg. Solar Irradiance ($KW/m^2/day$)	Avg. Relative Humidity (%)	Avg. Temp. (^oC)
206.14	1.40	3.66	74.75	20

VIII. CONCLUSIONS AND DISCUSSION

Implementing the proposed LNG regasification technology relying on solar energy as the power source will provide the industry with a sustainable environmental friendly solution; this proposed technique is expected to come up with the following advantages:

1. An efficient and productive LNG regasification technique, that will cut on the cost of the LNG regasification process, using solar power tower in which the solar power will be collected through mirrors and will be used to heat up an intermediate heating liquid (molten salt) which will heat up the humid air, which in turn will be blown through the heat exchangers of the LNG receiving terminals to vaporize the LNG.

2. As an added value to the NG power plants efficiency, the air resulting from the LNG regasification process will be cold dens dry air, which can improve the combustion of the attached gas turbines of the relevant power plants.

3. One of the expected valuable by-products in this proposed LNG regasification technique is the fresh water which will be as condensate resulting from the vaporization heat exchangers, for this plant it is expected to produce around 270 m^3/hour of plant operation; this chilled water can serve as fresh water source and for cooling applications.

4. The efficiency of collecting solar power through the floating mirrors is expected to be higher as the issue of dust accumulation on the mirrors will be minimized compared to the conventional onshore solar concentrating mirrors in case the plant is erected offshore, but of course the cost element should be considered.

IX. Limitations and Challenges

1. Relying on renewable resources such as solar may not be reliable everywhere and along the year due to the fluctuation of the availability of these resources, but for a climate like Houston it is promising and feasible technique.
2. Costly investment is needed to realize the proposed renewable powered LNG Regasification process compared to the conventional systems, but the expected pay back and low maintenance of the proposed system may make it the optimum choice for some areas which has a warmer and humid conditions such as in the USA, India, South East Asia, Southern Europe, the Middle East, and others where the LNG is used widely in power generation and there is an increasing demand for fresh water as well.

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