Journal of Modern Thermodynamics in Mechanical System
Volume 1 Issue 1

Analytical Modeling of Energy and Efficiency of Cryogenic Energy Storage Plant Using Various Working Fluids to Identify Best One for Load Shifting of Nuclear Power Plant and Renewable Energy Sources

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DOI: *http://doi.org/10.5281/zenodo.3381951*

Abstract
Cryogenic energy storage (CES) systems are good electricity storage method. In CES systems, excess current is used to liquefy gas. Liquid (cryogen) can be stored in large cryogenic tanks for a long time. Whenever there is demand for electric current, cryogen is warmed by waste heat to obtain gas. Gas so generated is then used to run gas turbine and generate electric current. Most researches are on air-based CES, as air is easily available. CES with other working fluids exhibit higher efficiency. In current modeling work, performance analysis of CES systems was done for different types of cryogens. Finally, it is concluded that CES with methane (natural gas) as the working fluid could exhibit highest efficiency.

Keywords: *Exergy, Electricity, Cryogenic Energy Storage, Methane, Natural Gas*

INTRODUCTION
Most important energy strategy is to increase the share of renewables in electricity production. All the renewable energy sources; for example, solar and wind energy, are intermittent; they rely highly on the weather. As a result, renewable energy production is not coherent with the demand for electricity. Intermittency makes replacement of the conventional power plants with renewable energy sources difficult. Stabilization of the electrical grid system with large share of renewables is possible with use of the energy storage systems. When the renewable energy is available, generated electricity is transformed into another form of energy that can be stored. If energy demand is high and not enough electricity is generated in power plants, energy can be unloaded from the storage. There are several technologies of electrical energy storage [1−5]. Only, cryogenic energy storage (CES) does not have any major drawbacks [6−11]. Fig.1 illustrates the working principle of CES: first stage of the process is the gas liquefaction; the off-peak electrical energy is used to liquefy cryogen, second stage is the storage of liquefied gas in the tank, while the last stage is energy recovery; liquid cryogen is pumped to higher pressure, heated using ambient and waste heat (if available) and expanded in a turbine.

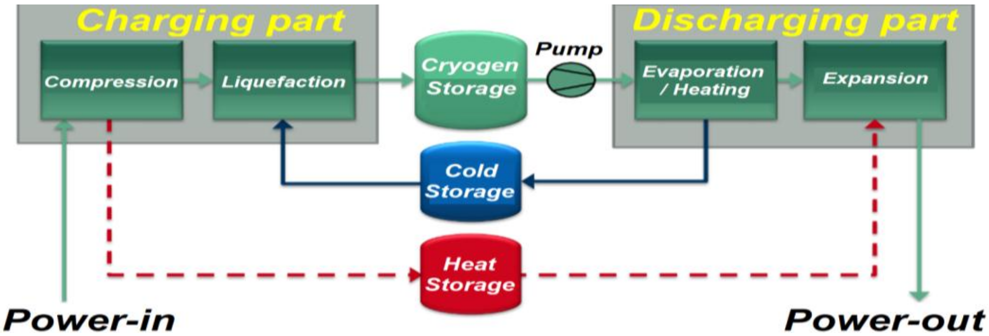

Figure 1: *Cryogenic energy storage.*

All of the mentioned stages are independent. At the system level, CES technology is not considered mature yet, however, all the components used in such systems have been used for many years in large gas liquefaction and separation plants.

MATERIALS AND METHODS

Defining energy and its density of cryogenic fluids, for calculating the specific energy of any cryogenic fluid, formula is: $e = T(s_a - s_l) - (h_a - h_l)$, where: T_a is an ambient temperature; s_a, h_a are specific entropy and enthalpy of cryogen at ambient conditions;s_l, $h_l$are liquid cryogen specific entropy and enthalpy respectively. Table 1 summarizes the energy density data of some cryogenic fluids (open literature data).

Table 1: *Energy of selected cryogens.*

Fluid	E (kJ/kg)	E (kJ/m^3)
Air	740	647
Nitrogen	769	620
Oxygen	635	725
Argon	477	666
Methane	1092	461

In cryogenic energy storage plant theoretical analysis, to compare mentioned cryogenic fluids, simple CES system shown in Fig.2 is considered. It consists of Joule-Thomson liquefaction facility, liquid cryogen tank (assumed to be perfectly thermally insulated) and power plant based on direct expansion cycle (with 2 turbine stages). In the analysis the temperature at the inlet of the gas to the liquefier compressor as well as to the gas turbines are ambient temperature (293 K) while the gas pressure at the inlet to the compressor and at the outlet from the last expander are 0.1MPa (ambient pressure). Table 2 summarizes the simulation parameters.

Table 2: *Liquefaction simulation parameters.*

Parameter	Value
Gas temp. at liquefier inlet (T_1)	293 K
Gas pres. at liquefier inlet (p_1)	0.1 MPa
Liquefied gas pressure (p_4)	0.1 MPa
Temp. at turbine inlet (T_6= T_8)	293 K
Pres. at turbine final outlet (p_9)	0.1 MPa
Turbines/pump η's @ ΔS=0	100%

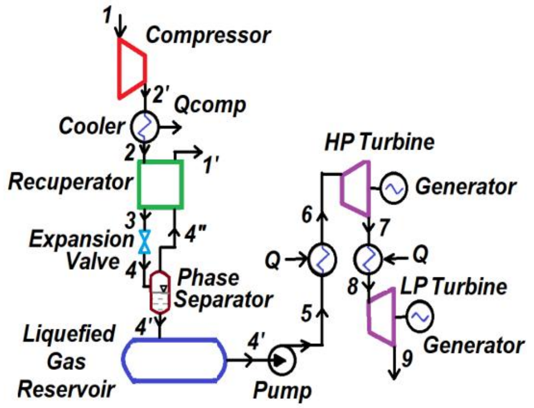

Figure 2: *Analyzed CES system.*

Analyzing liquefaction plant, it is worth noticing that energy density values shown in Table 1 are equal to minimal work of gas liquefaction. However, the real work of gas liquefaction can be several times higher than the ideal case, because of irreversibility that occur in real life liquefiers (in heat exchange processes, during throttling, as a result of friction, etc.) and heat from the surroundings. To compare the work of liquefaction, Joule-Thomson cycle (Fig.3) was used as one of the simplest liquefaction cycles. It consists of isothermal compression (process 1-2), cool down of compressed gas in the recuperative heat exchanger (2-3) and isenthalpic throttling (3-4). Part of the gas will liquefy (point 4') and will be stored in the liquefied gas tank, while the remaining stream (4") will flow through the recuperative heat exchanger (4"-1). $w_l = {}^{w_c}/_{y}$, where w_c is the work input to liquefier and y is the liquefaction yield of liquefier. The liquefaction yield of Joule-Thomson liquefier can be determined using heat balances of liquefier: $y = {}^{\dot{m}_l}/_{\dot{m}} = {}^{(h_1 - h_2)}/_{(h_1 - h_{4'})}$, where

$\dot{m}_l$ is the mass flow rate of liquid phase and $\dot{m}$ is the mass flow rate of gas at the inlet of liquefier. Work input to the liquefaction stage of the CES stage is equal to work of isothermal compression that can be found from: $w_c = \dot{m}[T_a(s_1 - s_2) - (h_1 - h_2)]$. Thus, work required to liquefy 1 kg of cryogen is then equal to: $w_l = \left[\frac{(h_1-h_2)}{(h_1-h_{4'})}\right][T_a(s_1 - s_2) - (h_1 - h_2)]$.

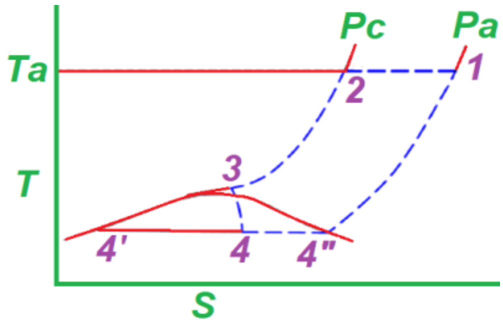

Figure 3: *Joule Thomson liquefaction cycle.*

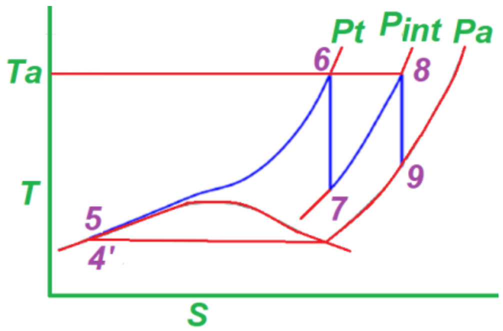

Figure 4: *Direct expansion of cryogen.*

In work extraction process, the simplest way to recover the energy stored in the liquefied gas is to perform the direct expansion cycle (Fig.4). At first, the liquid cryogen is pumped to high pressure (process 4'-5), then it is heated using ambient or, if available, waste heat (5−6). Finally the gas is expanded in two stages on the turbines (processes 6-7 and 8-9) driving an AC generator. In between high and low pressure turbines, the gas is reheated to the ambient temperature (7-8).

The intermediate pressure was obtained using formula: $p_{int} = \sqrt{p_t p_a}$. Specific work of turbines can be calculated as follows: $w_t = (h_6 - h_7) - (h_8 - h_9)$. Specific pump work can be determined in similar way: $w_p = h_5 - h_{4'}$. The network output is difference between works of turbine and pump: $w_{net} = w_t - w_p$. A typical T-s plot is given in Fig.5.

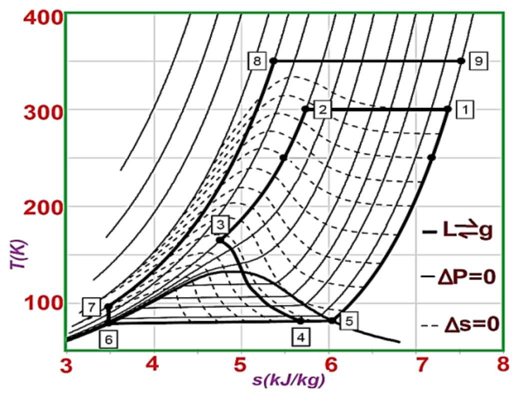

Figure 5: *Air temperature-entropy diagram.*

RESULTS AND DISCUSSION

To compare different working fluids for cryogenic energy storage, the following values were compared: liquefaction efficiency, work recovery efficiency and energy storage efficiency. The liquefaction efficiency (η_l) is the ratio of energy contained in liquid cryogen and the energy needed to liquefy it, i.e., $\eta_l = {}^{e}/_{w_l}$. The highest liquefaction efficiency can be achieved for methane (above 30%) while for other analyzed working fluids the maximum value of liquefaction efficiency was in the range of 13% to 22%. The liquefaction efficiency maximum of Joule-Thomson cycle is obtained for large compressor discharge pressure (p_2) values : around 35 MPa for methane, 30 MPa for air and nitrogen, 45 MPa for oxygen and argon. Recovery efficiency (η_r) is the ratio of network produced in cryogen expansion and the available energy of liquid cryogen: $\eta_r = {}^{w_{net}}/_{e}$. Fig.6 presents the recovery efficiency value of different types of the working fluids for different pressure at the turbine pressures. It can be found that the recovery efficiency values for each working fluid exhibit the maximum for a certain pressure at the inlet to the turbine. For the methane and argon this maximum is around 10 MPa while for the other gases the maximum is two or more times higher. It is also worth noticing that there is no large increase in recovery efficiency for turbine inlet pressures above 10 MPa.

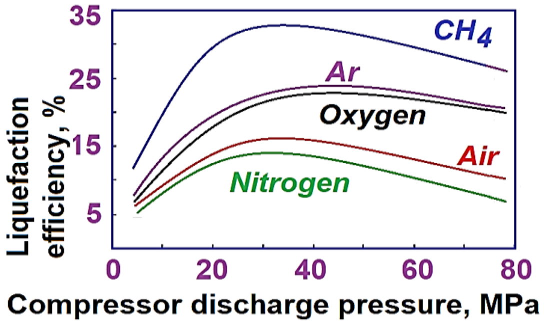

Figure 6: *Liquefaction efficiencies of cryogens.*

Finally, the storage efficiency (η_s) is the ratio of work of cryogen expansion and work of liquefaction: $\eta_s = {}^{w_{net}}/_{w_l}$. The storage efficiency was obtained for work of liquefaction (w_l) equal to minimal Joule-Thomson liquefaction work (maximal liquefaction efficiency – Fig.7). The highest storage efficiency (up to 12%) can be achieved for methane while for other analyzed gases this value is 2-4 times lower (around 7% for argon and oxygen, 5% for air and 4% for nitrogen), vide Fig.8. Efficiency values are very low in the analyzed system. Both liquefaction and gas expansion cycles used for the working fluids comparison are the most basic ones, and therefore, their liquefaction and recovery efficiencies are low. Further research should focus on more complex and more efficient liquefaction and cryogen expansion cycles.

Air is presently the most commonly used working fluid for the CES systems as it is available everywhere (therefore it does not limit the possible location of storage plant), and its thermodynamic properties are decent. Nevertheless, thermodynamic comparison of other cryogenic fluids shows that methane had the highest recovery efficiency and liquefaction efficiency and, therefore, the highest storage efficiency.

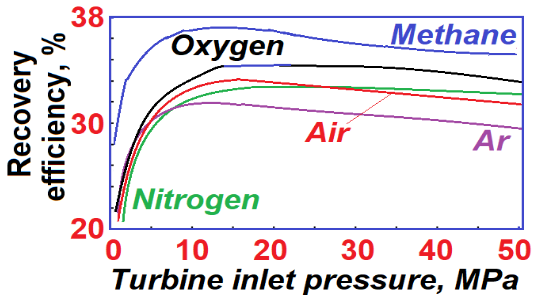

Figure 7: *Recovery efficiencies of cryogens.*

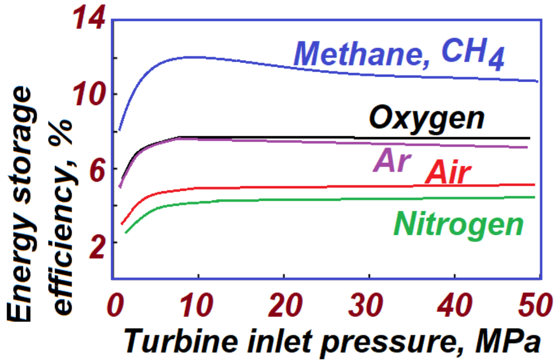

Figure 8: *Storage efficiencies of cryogens.*

Availability of natural gas for this purpose is high as natural gas pipeline networks in many countries are highly developed and LNG tanks are used to store natural gas instead of underground storage facilities [12]. This means that processed natural gas can be a promising working fluid in cryogenic energy storage systems. Other cryogens are generally not suitable for cryogenic energy storage because of the low efficiency and availability. Large recovery efficiency of methane and nitrogen indicate that energy recovery systems using the cold energy of liquid nitrogen (which is waste product from oxygen separation) or LNG (in LNG regasification stations [13, 14]) are promising technology. Presented cryogenic energy storage system is very basic, and its efficiency is very low. Joule-Thomson liquefaction cycle used in the analyzed storage system has low efficiency and requires high pressures. In more complex systems, Joule-Thomson cycle can be replaced with the one that utilizes expander instead of throttling valve.

Claude cycle and its modifications can provide much higher liquefaction yield and therefore higher liquefaction efficiency. Also, the cryogen expansion cycle used in the analysis can be replaced with another more complex one with higher efficiency. Nevertheless, the main disadvantage of a direct expansion cycle is that the thermal energy of the cryogen is destroyed in the heater (processes 5-6 and 7-8). There are few solutions for that problem. The cold from the expansion cycle can be stored and used in a liquefaction cycle to increase its efficiency. Additional cycles, such as Organic Rankine Cycle or Brayton cycle, can be incorporated using cryogen as low temperature heat source. Direct expansion cycle efficiency can be also increased by adding more turbine stages or by increasing $T_6$and T_8 temperatures using available waste heat sources (heat of compression from liquefaction cycle [15, 16] or waste heat available in thermal power plants or industrial processes). Waste cold (for example from the LNG evaporation process) may be used to improve the liquefaction yield of the plant. The most important problem to be solved in further research is to determine the best way of utilizing the thermal energy of the cryogen.

CONCLUSIONS

Air is presently the most commonly used working fluid for the CES systems as it is available everywhere (therefore it does not limit the possible location of storage plant), and its thermodynamic properties are decent. So, most CES researches focus on liquid air energy storage. CES with other working fluids exhibit higher efficiency. In current modeling work, performance analysis of CES systems was done for different types of cryogens. Nevertheless, thermodynamic comparison of other cryogenic fluids shows that methane had the highest recovery efficiency and liquefaction efficiency and, therefore, the highest storage efficiency.

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Cite this article as:
A Kanni Raj. (2019). Analytical Modeling of Energy and Efficiency of Cryogenic Energy Storage Plant Using Various Working Fluids to Identify Best One for Load Shifting of Nuclear Power Plant and Renewable Energy Sources. Journal of Modern Thermodynamics in Mechanical System, 1(1), 36–41. http://doi.org/10.5281/zenodo.3381951