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*Abstract***— Liquid Air Energy Storage (LAES) is a potential solution to mitigate renewable energy intermittency on islanded microgrids. Renewable microgrid generation in excess of the immediate load runs a cryogenic cycle to create and store liquid air. LAES systems can be combined with an expansion turbine to recover the stored energy. Using analytic methods to design a LAES and expansion system is complex and time consuming, suggesting modeling and simulation as a more efficient approach. Aspen HYSYS, an industrial process modeling software package, was used to model a combined Linde-Hampson cryogenic cycle (for liquefaction of air) and an expansion cycle (to convert the energy from liquid air vaporization to mechanical energy). The model was validated against previous analytic work. The validated model will be used to implement a model-based systems engineering (MBSE) approach to design an LAES and expansion system to reduce intermittency on an experimental microgrid at the Naval Postgraduate School in Monterey, CA, USA. Data from this facility will be used to further modify and validate the HYSYS model.**

Keywords—Liquid Air Energy, Microgrid, ASPEN HYSYS, Linde Cycle

I. INTRODUCTION

Increased use of renewable energy sources has created a motivation to explore new energy storage concepts to overcome the inherent intermittency problem. A Liquid Air Energy Storage (LAES) system stores excess renewable energy as liquid air, and then using the expansion of the liquid by flashing to vapor to create electrical energy for use when an energy deficit occurs. The system can maintain a storage of condensed vapor while energy from renewables is sufficient; but transitions to vaporization operations when energy from the renewables falls below a required threshold.

This technology is of particular interest to the United States Department of Defense (DoD) due to the rising cost of providing power to military units in garrison and afield. Two of the largest stakeholders within the US DoD are the United States Navy (USN) and the United States Marine Corp (USMC).

The USN has found that energy is the single largest cost for Naval Installations. The current Naval Installation shore budget dedicates 28% towards energy costs, the result being prioritization of reduction in energy costs and consumption [10]. The official program to address this issue is the Navy's "Shore Energy" program. Established in 2012, and defined in OPNAVINST 4100.5E it created an aggressive set of goals for energy control including, but not limited to, a reduction in greenhouse gas emissions, a reduction of 50% in energy consumption by 2020 and an achievement of 50% of all energy being supplied by renewables by 2020 [8].

The USMC has determined that the continued dependence upon fossil fuels is no longer an acceptable strategy, because it presents too much risk and limits operational reach [9] The USMC Expeditionary Energy Office (E2O), created in 2009, maintains an energy strategy in order to increase force effectiveness [6]. Alternative sources of power, such as solar, would reduce dependence on fossil fuels which require constant resupply from convoys to forward operating bases (FOBs). In 2010, these convoys supplied 200,000 gallons of fuel per day in Afghanistan, and the vulnerability of convoys resulted in a rate of one marine being wounded for every 50 convoys [6].

The Office of Naval Research (ONR) is currently funding exploration of an LAES system for integration into a building scale microgrid. Initial prototype construction and testing conducted by Naval Facilities Command Engineering (NAVFAC) and Nitro-Turbodyne Inc., resulted in two systems that failed to produce liquefied air [7]. Neither prototype design utilized modeling or simulation but instead depended only upon designs guided by first principles. The two prototypes have since been transferred to the Naval Postgraduate School (NPS). The goal is to analyze, redesign, build and test a new functional system.

In order to avoid the same results, a model-based system engineering approach was chosen to support design and construction of a small-scale prototype, with an eventual goal of an operational building-scale prototype. Model-based systems engineering is favorable since it is not feasible to continue to construct multiple prototypes and a validated model can inform the design process to increase the probability of a given prototype operating successfully [2]. However, validation of the model is necessary to verify its usefulness and accuracy in a model-based systems engineering approach. Previous published analytical solutions provide the comparative basis for model validation in this examination..

II. LAES and Expansion System

An LAES and expansion system combines the mature technologies of a cryogenic liquefaction with vaporization and expansion to drive a turbine for electrical power generation. Fig. 1 is a schematic of the combined cryogenic and expansion subsystems.

The cryogenic system utilizes a Linde-Hampson cycle that cools a working fluid in a heat exchanger (HX-1) and depressurization through a Joule-Thompson (JT) valve to liquefy vapor. The liquid reservoir stores the liquid and directs fluid, still in vapor form, back towards HX-1 for a regenerative cooling process. When electrical power generation is required, a pump moves the liquefied working fluid to HX-2 to vaporize it, followed by expansion through a turbine to turn a generator rotor.

A second heat exchanger, HX-1′, omitted in modeling, is shown in Fig. 1 and was included due to previous analytical studies exploring the effects of pre-cooling the working fluid prior to liquefaction. This secondary heat exchanger is not included in this examination because neither current prototype utilizes one and to simplify the modeling process in order to directly identify the conditions that must be achieved in order to obtain liquid air. Later model-based system engineering work will explore the best combination of components and scale to achieve the desired states.

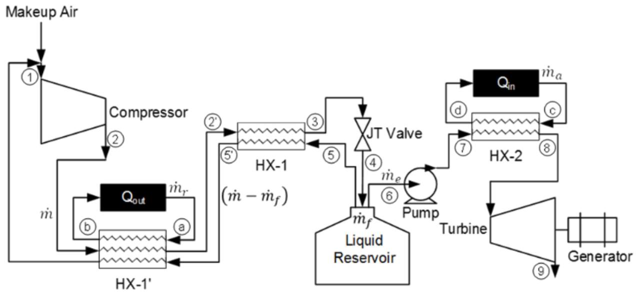

Fig. 1. Schematic of a Liquid Air Energy Storage and Expansion System [3]

III. Modeling Software

As a process modeling software utilized in the petroleum and chemical industries with a focus on asset optimization, Aspen HYSYS is a capable choice for designing a building-scale LAES and expansion system for a building-scale microgrid. Another benefit of the software is its integration into a suite of engineering software for detailed component design. Basic heat exchangers and their boundary conditions can be defined in HYSYS, and then exported to specialized software programs for detailed material and spatial design.

Preliminary modeling and simulation focused on the cryogenic cycle only [11]. This was done to ensure the software was suitable and accurate before moving to a complete system and because earlier modeling attempts were not validated. Joshi and Patel [5] modeled a Linde-Hampson cryogenic cycle in Aspen HYSYS but no fundamental comparison to any analytical solution was performed. The work of Howe [3] and Barron [1] were used as analytical baselines to compare our preliminary model to. The Peng-Robinson fluid package was found to be consistent with theoretical solutions for air to within fifteen percent. The air in the model consists of 80% nitrogen and 20% oxygen. Since future prototypes will utilize air, the Peng-Robinson fluid package was chosen for this work in spite of being less accurate than other fluid packages that are limited to single species analysis [11].

In the preliminary study the percent liquid yield was the fundamental comparison for validating modeling suitability. For the present work, the percent liquid yield was again verified as consistent, to ensure that changes to the simulation to incorporate the expansion phase had not made adverse changes in the cryogenic phase. An output of resulting liquid yields over varying compression ratios was created to compare and validate the full simulation. For the full model, the overall efficiency of the system will be utilized for validation. Howe previously had defined the efficiency as:

$$\eta_{sys} = \frac{\dot{W}_t}{\left({\dot{W}_C}/{Y}\right) + \dot{W}_p + \dot{W}_{HX_1{}'} + \dot{W}_{HX_2}} \quad (1)$$

Howe [3] model an ideal cycle. This equation was modified for this analysis to better fit real system design actions and to be consistent with the inherited prototypes in the hope they can be modified to function properly. Neither prototype featured a precooling heat exchanger (HX-1′). Thus, efficiency for this work was calculated using the equation:

$$\eta_{sys} = \frac{\dot{W}_t}{\dot{W}_C + \dot{W}_p} \quad (2)$$

The coolers in the model outlined in the next section are there to return working fluid streams to equilibrium conditions approximately to ideal conditions. This is needed to create simple stream conditions that can be modified for prototype design and scaling.

The simple software model from previous work was updated to approximate ideal isothermal operations by adding stages of compression and expansion. To achieve this isothermal compression and expansion a cooler or heater was included after a compressor or expansion turbine stage to return the working fluid to isothermal conditions. The pressure ratio for each stage, with n being the number of stages, was calculated by:

$$Presure\ Ratio = \frac{Outlet\ Pressure}{Inlet\ Pressure} = \sqrt[n]{\frac{Outlet\ Pressure}{Inlet\ Pressure}} \quad (3)$$

IV. HYSYS Model of LAES And Expansion System

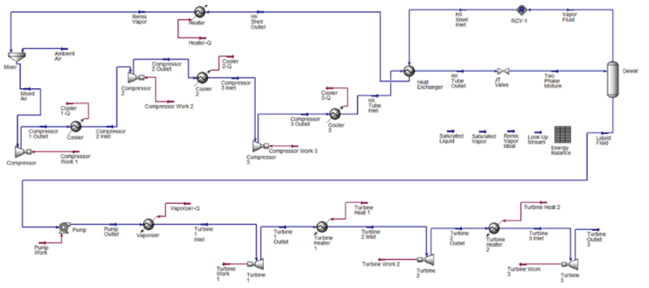

Fig. 2. Aspen HYSYS Model of LAES and Expansion System with 3-Stage Compression and Expanision

Fig. 2 is the software model built in Aspen HYSYS. The working fluid used in simulation is air and the fluid package was Peng-Robinson. Peng-Robinson uses a 26-term equation of state simulation package. These selections are consistent with future plans for a real world prototype as discussed earlier.

The functions of each component are as follows

- Mixer: Combines the recycled vapor returned from the dewar via the heat exchanger with makeup air from ambient.
- Compressor: Compresses the mixed air stream. This ratio is equal to that utilized by Barron and Howe in previous analytical evaluations. The compressor has a polyotropic efficiency of 100% and an adiabatic efficiency of 99.999%.
- Cooler: Approximates isothermal compression by cooling the material stream back to ambient temperature when used sequentially with the compressor.
- Heat Exchanger: An ideal heat exchanger that cools the material stream using recycled vapor from the dewar with zero pressure drop.
- JT Valve: Isentropically expands the material stream causing condensation of some of the material stream to liquid resulting in a two-phase mixture.
- Dewar: A separator that divides the vapor and fluid components of the two-phase mixture material stream.
- RCY-1: Recycle function that balances mass equation differences that result from software calculation rounding remainders.
- Heater: Heats recycled vapor back to ambient to mimic ideal cycle.
- Pump: Creates pump head to move liquid through expansion cycle. Discharge pressure ratio is 200:1 initially and the pump has an adiabatic efficiency of 100%.
- Vaporizer: Uses heat input to flash liquid nitrogen back to vapor.
- Turbine: Utilizes expansion of air vapor to produce mechanical energy.
- Turbine Heater: Returns material stream to inlet temperature to approximate isothermal expansion.

The Saturated Liquid, Saturated Vapor, Remix Vapor Ideal, Look Up Steam and Energy Balance are needed to overcome software limitations in approximating ideal systems. The pump was included to make the software more useful in later design phases. Currently, the prototype constructed by Nitro-Turbodyne, Inc. uses a check valve operated by differential pressure between the dewar and atmosphere. Since this system was never functionally demonstrated, it was decided to include a pump since most likely future prototypes would require one and to allow study of the trade space in re-pressurizing the air stream prior to expansion. It also allows for validation against previous work done by Howe.

Since this software model is meant to inform design and be verified against a constructed system prototype, the parts and streams were labeled to match real-world corollaries rather than keeping the labeling consistent with Fig. 1.

V. Results and Discussion

Some differences in the output were expected as a result of the modifications made for modeling. Howe [4] utilized isothermal compression in the cryogenic phase while the current work utilized isentropic compression. Isothermal compression in Aspen HYSYS would have to be approximated utilizing a series of compressors with intercooler. The present model approximates isothermal compression and expansion by have a cooler remove added heat from the working fluid post compression and a heater to add heat lost during expansion. This change will result in a lower expected efficiency for the simulation when fewer stages are utilized. The lack of precooling the working fluid prior to compression will also result in a lower efficiency. This is the reason why Howe included it in his energy analysis [4]. The limitations of the software will also result in a reduction in expected efficiency. Aspen HYSYS is an artifact based modeling software for real world systems. This puts some constraints on approximating ideal systems. For example, components do not function as intended when efficiency is forced to 100%. The expander utilized in the power generation system is set at 99.999% efficiency in order to function.

To verify continued accuracy of the fully developed model, the cryogenic cycle's liquid yield was verified against previous analysis. Fig. 3 illustrates the liquid yields obtain by varying State 2 pressure (State 2 is equivalent to HX Tube Inlet in Fig. 2). The results are consistent with previous modeling results for yield when utilizing the Peng-Robinson fluid package.

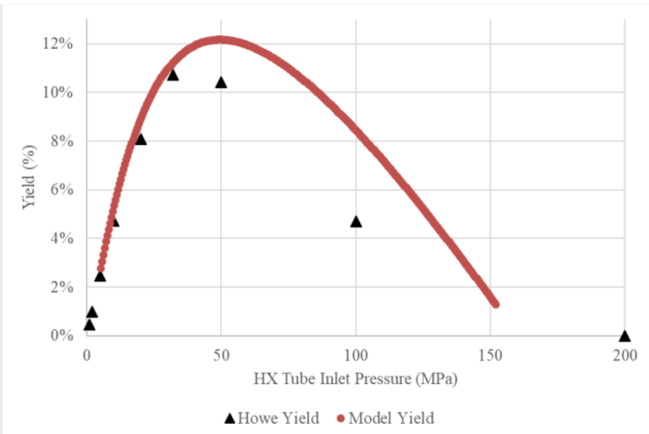

Fig. 3. Liquid Yield for Linde-Hampson Subsystem over Varying State 2 Pressures Adapted from Howe Pollman and Gannon [4].

The difference is explicable due to the difference in working fluid thermodynamic state tables utilized between the different simulations. Howe utilized tables from the National Institute of Standards and Technology (NIST) while this study used those tables intrinsic to the software. Since yields are consistent with previous examinations, this result is acceptable verification for continued model suitability.

The efficiency of the overall system was the final comparison to be used for software model validation. In his previous work, Howe developed performance tables for ideal system using varying pressure combinations for State 2 and State 7 (State 7 is equitable to Pump Outlet in Fig. 2). Both the model and Howe utilized air as the working fluid in the efficiency examination. The first model in the present study utilized single stage compression and expansion. This resulted in expected lower efficiencies due to the low fidelity in approximating isothermal compression and expansion. The temperature used in the first model was 300 K for State 2 (State 2 is equivalent to Mixed Air in Fig. 2).

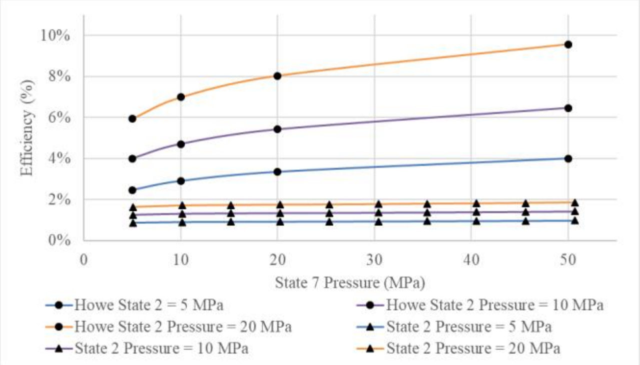

Fig. 4. Resulting LAES System Energy Efficiency over Full Range State 7 Pressure and Three Selected State 2′ Temperature and State 2' Pressures with 1-Stage Compression and Expansion. Adapted from Howe, Pollman and Gannon [4]

An advantage of Howe's ideal examination was the lack limitation on the maximum achievable pressures. Aspen HYSYS has limitations as to the max pressure for which the equations of states can be solved for. These limitations are consistent with those of real world components. Since a direct comparison of all values is limited, a qualitative matching of behavior and values obtained being on the same order of magnitude was considered acceptable. Fig. 4 shows that the efficiency of the system is much lower with only a single compression and expansion phase. The value shown from Fig. 4 is that even when varying the operating conditions of the system, the qualitative behavior of the model and theoretical solutions match.

To improve the fidelity of the model and approximate ideal conditions, the number of compression and expansion stages were increased. The pump outlet pressure was varied while the outlet pressure for the compression phase was held constant at 20 MPa.

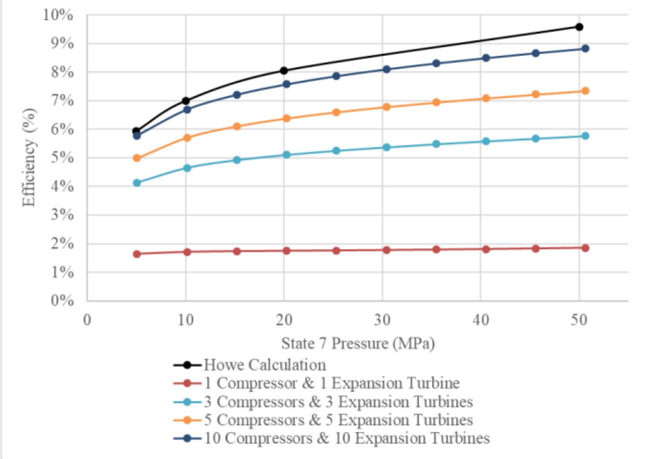

Fig. 5. Comparison of present work to previous LAES Storage and Expansion System Efficiencies at 20 MPa State 2' Pressure. Adapted from Howe, Pollman and Gannon [4]

TABLE I. EFFICIENCIES OF THEORETICAL SOLUTION VERSUS ASPEN HYSYS MODEL EFFICIENCY. ADAPTED FROM HOWE, POLLMAN AND GANNON [4]

Number of Stages	Conditions	Howe Efficiency (%)	Model Efficiency (%)
1	State 2 & State 7 Pressure = 20 MPa	8.05	1.75
10	State 2 & State 7 Pressure = 20 MPa	8.05	7.57

Fig. 5 illustrates that the overall efficiency of the system increases as the number of compression and expansion stages increase. This is consistent with expected behavior for a model that approximates isothermal process with greater fidelity. As expected the improvement in efficiency for each added stage decreases; the improvement from three to five stages is greater than that from five to ten stages. The model approximates the theoretical solution, and will approach the ideal system as the number of compression and expansion stages approaches infinity.

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