Investigating the Effects of Boil-off Gas on Liquefied Energy Carriers During Land Storage and Ocean Transportation

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Abstract. As the largest energy production suppliers are in different locations of the world and the demand for energy increases significantly, storage and transportation of large-scale energy with high storage and transportation efficiencies are desired. Large-scale energy is stored and shipped in liquefied forms due to reduction in volume however storage medium in a liquid form with low boiling temperature loses some of its energy because of evaporation, called boil-off gas (BOG), which is caused by a change in temperature between the storage medium and the ambient. Therefore, this study presents sensitivity analysis for three types of energy carriers: liquefied natural gas (LNG), dimethyl-ether (DME), and methanol to store and transport energy in liquid form from an exporting country to an importing country. A calculation method is used to determine the daily BOG rates accounting for storage and transporting for the three liquefied energy carriers. A sensitivity analysis is presented to reveal the effects of changes in duration of land storage and ocean transportation on the total stored and transported masses. LNG has lost 7% of its mass as BOG after 60 day of shipping and this lost percentage is the highest compared to DME and methanol. Due to low mass loses during storage and transportation phases, methanol and DME are potential alternatives for storage and transportation of large energy quantities.

1. Introduction
The need for effective and efficient energy carriers arises due to increase in demand for energy in various locations of the world where best suited regions for energy production are often far away from demanded regions. Consequently, long duration of land storage and overseas transport of energy is required. Large-scale energy carriers are usually converted into liquefied form to reduce their volumes as the case of liquefied natural gas (LNG) where natural gas is liquefied into LNG which results in reduction of its volume by about 600 times [1]. Due to this advantage, researchers have proposed different energy carriers to store and transport energy in liquefied form. Hydrogen is a promising energy carrier due to low environmental impacts since carbon-free [2]. However, storing hydrogen has several challenges. Hydrogen can be converted into dimethyl ether (DME) and methanol, which are petrochemical products that appear to be alternatives for carrying large-scale energy [3]-[5]. Even though these energy carriers in liquefied form store and transport more energy compared to other forms of energy, storage and transportation medium in liquefied form lose some of it is mass because of temperature difference between the environment and the medium. These losses from energy carriers in liquefied form are called boil-off gas (BOG). The BOG generation occurs in different stages of an energy carrier supply chain but mainly in land storage and ocean transportation phases [6]-[9]. Therefore, this paper proposes three energy carriers: LNG, DME and methanol to store and transport...
energy in liquefied form. A calculation method is implemented to determine the BOG generation in each energy carrier during land storage phase and ocean transportation phase and sensitivity analysis is implemented to observe how duration of land storage and ocean transportation affect the total stored and transported mass.

2. System description
The study includes three energy that are used to transport the energy in large quantities from supplied regions to demanded regions. After production of these energy carriers either by renewables or nonrenewable resources, they are initially liquefied (if not in liquid form at storage conditions) for the purpose of reducing the volume size, and then stored in large land storage tanks. The land storage tanks are cryogenic tanks which maintain the energy carriers under their boiling temperatures. The temperature difference between the environment and the medium inside the tank causes heat ingress moving through the tank walls which causes generation of BOG inside the tank. Once the land storage tank is filled, the energy carriers are pumped into the ship tanks for ocean transportation. Insulated tanks are mounted in the ship hull to keep the energy carriers in their liquefied forms. Even though the ship tanks have insulation resistivity, BOG generation still occurs due to heat ingress into the ship tank and sloshing of cargo because of the wave movements in the ocean. Therefore, a calculation method is used to determine the BOG generation during land storage and ocean transportation for LNG, DME and methanol. Since the duration for land storage and ocean transportation is changing due to production capacity and variety of distances between the supplier and the demander, sensitivity analysis is implemented. The generation of BOG (lost mass during land storage and ocean transportation) is calculated under different land storage duration and ocean transportation duration. Hence, to make fair comparison between LNG, DME, and methanol as energy carriers, the ship volume is fixed to 160,000 m³. See figure 1

![Figure 1](image-url)  
Figure 1. The BOG generations during land storage and ocean transportation of energy carriers.

3. Analysis
The thermophysical parameters for LNG, DME, and methanol at atmospheric pressure and temperature of 1 bar and 25 °C are shown in Table 1. The thermophysical parameters are obtained using the software Engineering Equation Solver [10].

| Thermophysical Properties | LNG   | DME   | Methanol |
|---------------------------|-------|-------|----------|
| Storage Temperature (°C)  | -162  | -25   | 5        |
| Density (kg/m³)           | 423.1 | 735.5 | 805      |
| Mass for Single Tank (kg) | 16,924,000 | 29,420,000 | 31,640,000 |
| Δhvap (kJ/kg)             | 511.8 | 465.6 | 1199     |
Determining the BOG generation during the land storage and ocean transportation emphasizes the mass lost in each energy carrier. As the main source of the BOG generation in the land storage and ocean transportation is the heat ingress from the surrounding into the tanks, ingress is calculated by determining the tank area, difference in temperature between the medium and the environment, and the heat transfer coefficient of the tank. The heat ingress is shown in equation 1.

\[ \dot{Q} = UA\Delta T \]  

where \( \dot{Q} \) represents the heat ingress in W, \( U \) is the overall heat transfer coefficient for the tank, \( A \) is the surface area in m\(^2\) and \( \Delta T \) is the temperature difference between the tank and the surrounding in K. The heat transfer coefficient for the land storage tank is 0.114 W/m\(^2\)K \[11\] where the heat transfer coefficient for the ship tank is 0.2 W/m\(^2\)K \[12\], and the surface area is 5660 m\(^2\) for spherical storage tank with a radius of 21.23 m. While the energy carrier evaporation is the ratio between the heat ingress into the tank and the heat of vaporization (\( \Delta h_{vap} \)) as presented in equation 2.

\[ \text{Energy carrier}_{\text{Evaporation}} = \frac{\dot{Q}}{\Delta h_{vap}} \]  

Hence, the land BOG generation for an energy carrier for land storage and ocean transportation is calculated by equation 3.

\[ \text{BOG_{land, ocean transportation}} = \frac{\text{Energy carrier}_{\text{Evaporation}}}{\text{Energy carrier}_{\text{storage}}} \]  

Once the BOG daily generation rates are determined for LNG, DME, and methanol, sensitivity analysis is implemented using Engineering Equation Solver on changing the land storage duration and ocean transportation duration.

4. Results and discussion

The BOG daily rates for LNG, DME, and methanol in liquefied form are presented in Figure 2. LNG has the highest BOG rates in both land storage and ocean transportation phase compared to DME and methanol because of the low temperature of LNG (-162°C). DME and methanol have BOG rates of less than 0.01% per day in land storage and ocean transportation, which show DME and methanol lose less of the carried energy as BOG compared to LNG. Therefore, DME and methanol can be alternatives with low losses for large quantities of energy storage and transportation.

\[ \text{Energy Carriers} \rightarrow \text{Land Storage} \rightarrow \text{Ocean Transportation} \]

\[ \begin{array}{c}
\text{LNG} \rightarrow 0.211\% \text{ BOG} \\
\text{DME} \rightarrow 0.035\% \text{ BOG} \\
\text{Methanol} \rightarrow 0.005\% \text{ BOG}
\end{array} \]

\[ \begin{array}{c}
\text{LNG} \rightarrow 0.12\% \text{ BOG} \\
\text{DME} \rightarrow 0.02\% \text{ BOG} \\
\text{Methanol} \rightarrow 0.002\% \text{ BOG}
\end{array} \]

**Figure 2.** Daily BOG rates for LNG, DME and methanol during land storage and ocean transportation.
Since BOG is generated in the tanks during land storage and ocean transportation, Figure 3 shows slight reduction in energy carriers’ masses as the land duration increases. For example, to store LNG for 30 days without utilization of BOG and just evaporate to the environment causes around 6% reduction of LNG mass. While DME and methanol lose about 1% and 0.15% of their masses as BOG after 30 days of land storage, respectively.

![Figure 3](image1.png)

**Figure 3.** Effects of change in land storage duration on the total available mass.

The effects of increasing the duration of ocean transportation of the mass carried by the energy carriers are presented in Figure 4. As the duration of ocean transportation increases, generation of BOG increases which results in decreased delivered mass from a supplied region to a demanded region. LNG has lost 7% of its mass as BOG after 60 day of shipping and this lost percentage is the highest compared to DME and methanol due to the high daily BOG rate during ocean transportation. Moreover, the energy carriers lose more of their masses in ocean transportation phase than land storage phase. Due to low mass loses during storage and transportation, methanol and DME are potential alternatives for storage and transportation of large energy quantities.

![Figure 4](image2.png)

**Figure 4.** Effects of change in ocean transportation duration on the total available mass.
5. Conclusion
As the production capacity of energy increases due to demand increase, effective and efficient energy carriers are preferred for large scale storage and transportation of energy. LNG, DME, and methanol are energy carriers and they are proposed to be stored and transported in liquefied forms. The lost masses each energy carriers during land storage phase and ocean transportation are presented, and sensitivity analysis is carried out to observe the lost masses as BOG during the land storage and ocean transportation. DME and methanol can become alternatives after considering the cost and environmental impacts as well to transport energy since their daily BOG rates are lower compared to LNG.

6. References
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