A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage – Part 4: Sensitivity analysis of transport pressures and benchmarking with conventional technology for gas transport

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ABSTRACT

A novel energy and cost effective transport chain for stranded natural gas utilized for power production with CO_2 capture and storage is developed. It includes an offshore section, a combined gas carrier and an integrated receiving terminal. In the offshore section, natural gas (NG) is liquefied to LNG by liquid carbon dioxide (LCO_2) and liquid inert nitrogen (LIN), which are used as cold carriers. In the onshore process, the cryogenic exergy in the LNG is utilized to cool and liquefy the cold carriers, LCO_2 and LIN. The transport pressures for LNG, LIN and LCO_2 will influence the thermodynamic efficiency as well as the ship utilization; hence sensitivity analyses are performed, showing that the ship utilization for the payload will vary between 58% and 80%, and the transport chain exergy efficiency between 48% and 52%. A thermodynamically optimized process requires 319 kWh/tonne LNG. The NG lost due to power generation needed to operate the LEC processes is roughly one third of the requirement in a conventional transport chain for stranded NG gas with CO_2 capture and sequestration (CCS).

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1. Introduction

The liquefied energy chain (LEC) is a novel energy and cost effective transport chain for stranded natural gas utilized for power production with CO_2 capture and storage, which includes an offshore section, a combined gas carrier, and an integrated receiving terminal, see Fig. 1. In the offshore section, natural gas (NG) is liquefied to LNG by liquid carbon dioxide (LCO_2) and liquid inert nitrogen (LIN), which are used as cold carriers. The nitrogen is emitted to the atmosphere at ambient conditions. The CO_2 at high pressure is transferred to an offshore oilfield for enhanced oil recovery (EOR). LNG is transported to the receiving terminal in the combined carrier.

At the receiving terminal, the cryogenic exergy in LNG is recovered by liquefaction of CO_2 and nitrogen. The onshore process is connected to an air separation unit (ASU) that produces nitrogen for the offshore process and oxygen for an oxyfuel power plant,

where NG is converted to electricity, CO_2 and water. The water is removed by condensation from the CO_2 which is compressed to a pressure above the triple point (TP) and liquefied by vaporization of the remaining LNG. The LCO_2 and LIN are transported offshore in a combined gas carrier. Transporting CO_2 and LNG in the same ship results in an enhanced ship utilization. This paper is the last in a series of four papers that describe the liquefied energy chain. The first paper describes the concept and summarizes the results from the remaining three [1]. The second paper addresses the offshore and onshore processes [2]. The third paper describes the combined carrier [3]. This paper contains a general description of the thermo-mechanical exergy of LNG, LIN and LCO_2, sensitivity analyses of the ship utilization and exergy efficiencies as a function of transport pressures, as well as a benchmarking against conventional technologies for gas transport.

2. Methodology and exergy analysis

The calculations in the first section of this paper, a general description of the effect of transport pressure, are based on pure

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Nomenclature

ε	specific exergy
$\varepsilon^{(T)}$	temperature based specific exergy
$\varepsilon^{(P)}$	pressure based specific exergy
$\varepsilon_i^{(ch)}$	specific chemical exergy for component i
$\varepsilon^{(ch)}$	total specific chemical exergy
E	exergy supplied or removed from the system
$\Delta_f G°$	standard Gibbs free energy of formation
h	specific enthalpy
i	component
j	stream
m	mass flow
p	product
r	reactant
R	universal gas constant
s	specific entropy
T_0	ambient temperature
X	mole fraction

Ψ	the exergy (rational) efficiency
$\Psi_{conversion}$	the exergy conversion efficiency
ASU	air separation unit
CCS	carbon capture and sequestration
EOR	enhanced oil recovery
FPSO	floating production, storage and offloading vessel
HP	high pressure
LCO_2	liquid carbon dioxide
LEC	liquefied energy chain
LHV	lower heating value
LIN	liquid inert nitrogen
LNG	liquefied natural gas
LP	low pressure
ppm	parts per million
TP	triple point
SUF	ship utilization factor

components, and the data are collected from NIST [4]. In the rest of the paper, the processes are simulated in HYSYS [5], using the SRK equation of state. SRK is used as it is a well known EOS for calculation of light hydrocarbons and pure components. We have tested other EOS, and the deviation is marginal. However, if a mixture of water, hydrocarbons and CO_2 is to be separated, the deviation will be very large. The NG composition is lean and consists of 1% nitrogen, 92% methane, 5% ethane, 1.8% propane and 0.2% butanes. Impurities such as mercury, water and CO_2 are assumed not present in the feed gas. The CO_2 and nitrogen streams are treated as pure gases. All processes are based on state-of-the-art equipment with standard industrial efficiencies. Additional information about of the simulation tools, equipment and ambient data can be found in the detailed description of the processes [2].

Neglecting the contributions from kinetic and potential energy and having no reactions in or mixing of the fluids, the specific change of exergy in a stream j through a unit and the exergy (rational) efficiency can be expressed as [6]

$$\Delta \varepsilon_j^{(tm)} = (h_{Outlet} - h_{Inlet})_j - T_0(s_{Outlet} - s_{Inlet})_j = (\varepsilon_{Outlet} - \varepsilon_{Inlet})_j \quad (1)$$

$$\Psi = \frac{\sum_{out} m_{out} \varepsilon_{out} + E_{out}}{\sum_{in} m_{in} \varepsilon_{in} + E_{In}} \quad (2)$$

In Eqs. (1) and (2), ε is the specific exergy, h is the specific enthalpy, s is the specific entropy and m is the mass flow of a stream. E is the exergy supplied or removed from the system. T_0 is the ambient temperature. The exergy (rational) efficiency, Ψ, describes the fraction of the input exergy (available energy) in a process that is converted

to useful exergy. The exergy conversion efficiency is defined as the exergy efficiency taking into account only the exergy components that change throughout the process. In a steady-state NG process with no mixing, separation or chemical reactions, the conversion exergy efficiency will neglect the chemical exergy and focus on the thermo-mechanical components. Hence, the conversion exergy will be lower, but more representative, than the total exergy efficiency which includes the chemical components in both the inlet and the outlet streams (see Fig. 2).

In thermodynamics, the exergy can be divided into physical and chemical exergy. The physical exergy can be further divided into mechanical exergy, which is normally neglected in process calculations, and thermo-mechanical exergy. The thermo-mechanical exergy component can be split into temperature and pressure based exergy. The temperature based exergy $\varepsilon^{(T)}$ is defined as the maximum obtainable work when a system, such as a stream is brought from its current temperature (T) to ambient temperature (T_0) at constant pressure (P). Pressure based exergy $\varepsilon^{(P)}$ is the maximum obtainable work when the stream is brought from its current pressure (P) to ambient pressure (P_0) at ambient temperature (T_0), hence [6]

$$\varepsilon^{(T)} = h(T, P) - h(T_0, P) - T_0(s(T, P) - s(T_0, P)) \quad (3)$$

$$\varepsilon^{(P)} = h(T_0, P) - h(T_0, P_0) - T_0(s(T_0, P) - s(T_0, P_0)) \quad (4)$$

If ideal gas with constant heat capacity C_p is assumed, the expressions for temperature (Eq. (5)) and pressure based exergy (Eq. (6)) become [6]
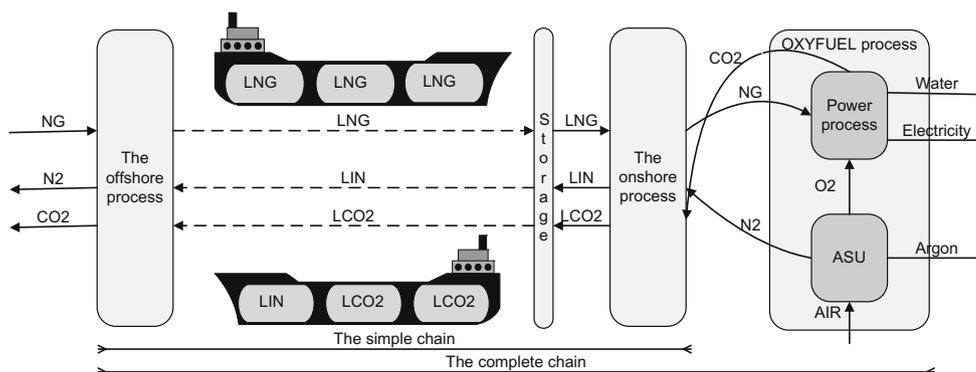

Fig. 1. The liquefied energy chain.