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An economic and environmental assessment of transporting bulk energy from a grazing ocean thermal energy conversion facility

Elisabeth A. Gilmore [a,*], Andrew Blohm [a], Steven Sinsabaugh [b]

[a] School of Public Policy, University of Maryland, College Park, MD 20742, USA
[b] Lockheed Martin MST New Ventures, Baltimore, MD 21220, USA

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A B S T R A C T

An ocean thermal energy conversion (OTEC) facility produces electrical power without generating carbon dioxide (CO_2) by using the temperature differential between the reservoir of cold water at greater depths and the shallow mixed layer on the ocean surface. As some of the best sites are located far from shore, one option is to ship a high-energy carrier by tanker from these open-ocean or "grazing" OTEC platforms. We evaluate the economics and environmental attributes of producing and transporting energy using ammonia (NH_3), liquid hydrogen (LH_2) and methanol (CH_3OH). For each carrier, we develop transportation pathways that include onboard production, transport via tanker, onshore conversion and delivery to market. We then calculate the difference between the market price and the variable cost for generating the product using the OTEC platform without and with a price on CO_2 emissions. Finally, we compare the difference in prices to the capital cost of the OTEC platform and onboard synthesis equipment. For all pathways, the variable cost is lower than the market price, although this difference is insufficient to recover the entire capital costs for a first of a kind OTEC platform. With an onboard synthesis efficiency of 75%, we recover 5%, 25% and 45% of the capital and fixed costs for LH_2, CH_3OH and NH_3, respectively. Improving the capital costs of the OTEC platform by up to 25% and adding present estimates for the damages from CO_2 do not alter these conclusions. The near-term potential for the grazing OTEC platform is limited in existing markets. In the longer term, lower capital costs combined with improvements in onboard synthesis costs and efficiency as well as increases in CO_2 damages may allow the products from OTEC platforms to enter into markets.

1. Introduction

Ocean thermal energy conversion (OTEC) facilities produce electrical power by exploiting the temperature difference between the shallow mixed layer on the ocean surface and the reservoir of cold water at greater depths to run a heat engine. OTEC facilities were first investigated in the 1970s and 1980s as a response to spikes in fuel prices [1]. More recently, there has been renewed interest in OTEC facilities due to concerns about energy security, policies to reduce carbon dioxide (CO_2) emissions that contribute to climate change, and innovations that have reduced the cost of many of the components [2]. However, there are a limited number of regions with resources that are sufficiently close to onshore markets that can make direct use of the electricity from the OTEC facility via high voltage alternating or direct current (HVAC/HVDC) transmission lines, for example Hawaii [3]. Additionally, more favorable temperature differentials between the surface and deep waters are found further offshore in the Atlantic and Pacific oceans [4]. It is possible to design OTEC platforms that "graze" in these zones; however, the viability of these OTEC platforms depends on the availability and cost-effectiveness of options for transporting the stranded energy to markets.

Here, we evaluate the economics and environmental attributes of producing and transporting energy from a grazing OTEC platform using ammonia (NH_3), liquid hydrogen (LH_2) and methanol (CH_3OH). Several applications have been considered for OTEC facilities, including high-energy fuels [5], batteries [6] and energy intensive industrial processes such as aluminum production [1] and desalination [7]. For long distance transportation, high-energy carriers such as NH_3, LH_2 and CH_3OH receive the most attention, as there are existing markets or may be near-term markets for these products. For example, Van Ryzin et al. considers using OTEC facilities for a hydrogen-based economy [8]. These carriers would be

* Corresponding author. Tel.: +1 301 405 6360.
E-mail addresses: gilmore@umd.edu (E.A. Gilmore), andymd26@umd.edu (A. Blohm), steven.sinsabaugh@lmco.com (S. Sinsabaugh).

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transported to shore in an ocean tanker and then sold directly or used as a fuel to produce electricity and other products onshore [9]. These additional transformations and transportation, however, come at a cost and affect the CO_2 and other air emissions associated with the final product. Thus, assessing the potential for these bulk energy carriers requires an evaluation of the costs of producing and transporting the carrier, the prices and size of the market for the product, and a comparison of the CO_2 emissions associated with the product from the OTEC facility and the existing production processes. While there is presently no global policy that places a monetary value on CO_2, there are estimates of externalities – damages that are not priced in existing markets – associated with CO_2 emissions [10]. Monetizing the adverse impacts from CO_2 emissions allows us to evaluate the full cost of the energy carriers, where the full cost is defined as the cost of production and the externalities. The presence of externalities can lead to future regulations as a divergence between the costs of production and the social costs is a strong justification for intervention.

Our work builds on previous efforts to evaluate the costs, safety and environmental emissions associated with shipping energy over a range of pathways [11]. For example, Bergerson and Lave compared transporting energy as coal via rail, coal gas via pipeline or electricity via wire from the Powder River Basin in Wyoming to Texas on the basis of the costs, environmental characteristics and public safety risks of these options [12]. They found that the preferred mode of transportation was a function of distance as well as the existing infrastructure and the quantity of the carrier that was being shipped. Oudalov et al. extended this into a broader framework across rail, vessels, pipelines, trucks, HVAC and HVDC lines for a range of primary energy resources [13]. This model also broadened the range of externalities to include air emissions, safety hazards, noise impact, visual impact and electromagnetic fields (EMF). While this model allows wind and solar energy to be transported as hydrogen (H_2) in a number of transportation modes including vessels, this model did not envisage the range of energy carriers considered for an OTEC facility. Thus, this work extends the literature on the costs and impacts of long distance transport of bulk energy.

2. Materials and methods

To evaluate the potential for bulk energy products, we first calculate the variable costs of producing the product using the grazing OTEC platform and transporting it to market. We then compare the difference between the market prices and the variable cost of production using the grazing OTEC platform to the capital and fixed costs of the OTEC platform and the synthesis equipment. Second, we identify and quantify the externalities associated with both the OTEC platform and the onshore processes to compare the products on a full cost basis. We focus on CO_2 as this is the likely driver for the increased use of renewable energy. Finally, we conduct a full sensitivity analysis to identify opportunities, namely technological improvements, market potential and policy regimes that would enhance the economics of OTEC platforms and the energy pathways. We develop our model in Analytica. This software allows us to build a fully parametric model and isolate the variables that are most likely to influence the decision [14]. Details of the Analytica software can be found in Ref. [15]. In this model, we start with the decision to build an OTEC platform followed by the selection of energy carrier. Each carrier is associated with a transportation pathway that consists of the following elements: a product synthesis technology on the OTEC platform; a transportation method to available markets; additional onshore infrastructure (if needed); and market potential and prices at delivery. Here, we describe the methods and data used to develop the costs as well as the technological and environmental characteristics of these pathways.

2.1. Grazing OTEC platform

To calculate the capital costs of an open-ocean, also known as grazing, OTEC platform, we draw upon the most recent literature as well as analyses conducted for Lockheed Martin [16]. We show all prices in US dollars (USD) 2012. The capital costs that we use are for a first of a kind unit. Generally, increases in installed capacity lead to reduced capital costs. While we present our results using the first unit costs, we conduct a bounding analysis of an approximate 25% reduction in the capital cost of the OTEC platform and the onboard synthesis equipment. We estimate this bound as ten years of improvements at approximately 3% per year. This rate is consistent with the empirical evidence [20]. Additionally, the capital cost of the OTEC platform is related to the capacity as well as the temperature differential at that location. We apply capital cost estimates for OTEC platforms of two different sizes in the Western Atlantic and Western Pacific oceans. For the same net generation, platforms in the Atlantic have a higher capital cost than those in the Pacific due to the lower temperature differential. We estimate that the resource quality and other site-specific factors result in a difference in capital costs of approximately 7%. We also consider fixed annual costs for maintenance for the OTEC platform. We estimate these maintenance costs at approximately 4% of the capital costs for the OTEC platform. Additionally, there are variable operating and maintenance costs (e.g. costs that are incurred as a function of production); however, these are likely small compared to the fixed costs.

2.2. Development of energy transportation pathways

There are a number of potential bulk energy carriers available to transport the energy from an OTEC platform to existing and near-term markets. We start by screening these potential energy carriers on their costs and the technological maturity of synthesis on an OTEC platform, the available transportation options to bring the product to shore, the availability of onshore receiving facilities, and the market prices, size and potential.

Through a thorough literature review of the available carriers, we identify anhydrous ammonia (NH_3), liquid hydrogen (LH_2) and methanol (CH_3OH) as the most promising energy carriers. We base our selection on three criteria. First, we require that the synthesis technologies for production on an open-ocean OTEC platform are commercially available. Second, there must be ocean tankers or designs for ocean tankers as well as port infrastructure for these products at several US and international ports. Third, the markets for these products need to be large and transparent in terms of prices (i.e., the markets are competitive). We observe that the transportation and markets for LH_2 are less well developed, although there may be near-term potential depending on independent developments in the energy system. In Supplementary Data (Section S1), we present an overview of the three energy carriers that are considered in this manuscript as well as other potential options.

For these three energy carriers, we develop a techno-economic model of the production, transportation, onshore conversion and delivery to market. We use this model to identify the capital, fixed and variable costs, efficiencies, emissions and other externalities associated with the transportation pathway. We describe the data for each stage below. We focus on selling the products directly into markets. However, there is also the possibility of converting NH_3 and H_2 onshore into electricity via combustion and fuel cells [17] or producing fuel for transportation (e.g. CH_3OH to gasoline) [18].