Renewable Energy 71 (2014) 361–367

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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

ARTICLE INFO

Article history:
Received 20 August 2013
Accepted 13 May 2014
Available online

Keywords:
Ocean thermal energy conversion (OTEC)
Ammonia
Liquid hydrogen
Methanol
Onboard synthesis
Market analysis

ABSTRACT

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).

http://dx.doi.org/10.1016/j.renene.2014.05.021
0960-1481/

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].

These energy carriers have also been evaluated for potential contributions to larger transformations of the energy and transportation sectors (e.g. Ref. [19]). We do not consider these types of pathways in this analysis as it would require projections of future energy systems.

2.2.1. Onboard product synthesis

For each energy carrier, we identify the synthesis equipment, the overall synthesis efficiency from electricity from the OTEC platform in kWh to product in metric ton, and the capital and maintenance costs for the equipment. A unit that electrolyzes water to produce hydrogen (H_2) is required for the production for NH_3, LH_2 and CH_3OH. For NH_3 synthesis, an air separation unit to produce nitrogen (N_2) and a Haber–Bosch synthesizer and associated compressors, circulators and refrigeration are also needed. The synthesis of CH_3OH also necessitates additional units to gasify coal to produce carbon monoxide (CO) as well as associated compressors, circulators and refrigeration. The coal must also be delivered from shore to the gasification units. We do not include the full technical details of each pathway in this manuscript, rather we refer the reader to references [5,9,16].

For the product synthesis, we show our central cost estimate and the range of efficiencies in Table 1. For efficiency, we calculate a range in kWh per metric ton of product. The efficiency is largely driven by the electrolysis of H_2 where we apply a range of 50–90% based on the high heating value (HHV) of H_2. We use 75% as our base case estimate. The efficiency for LH_2 includes the energy penalty for compressing the H_2 estimated at 13,000 kWh/metric ton of product. For the capital cost, we consider the capital and variable costs of the energy carrier synthesis equipment. We apply estimates for the capital costs of synthesis and efficiency from Lockheed Martin for NH_3. For H_2 and CH_3OH, we adapt capital costs and efficiency from Avery et al. [5]. To update these estimates of the capital costs to present dollars (2012 USD), we employ a two-step process. First, we apply a factor to account for technological progress of approximately 3% per year [20]. Second, we correct this value from 1985 to 2012 dollars using the Producer Price Index for Chemical and Allied Products (PPI-CAP) from the US Bureau of Labor Statistics (BLS) [21]. We also consider fixed annual costs for maintenance for the OTEC platform and synthesis. We estimate these maintenance costs at approximately 10% of the capital costs for the synthesis equipment. Similar to the OTEC platform, we assume that the variable operating and maintenance costs are small compared to the fixed costs.

2.2.2. Transportation and onshore conversion

The majority of the variable costs for each product are found in the shipping from the OTEC platform to the market via ocean tanker. Most shipping costs are set through long-term contracts [22]. These contracts are proprietary and are established by product and by route, making it difficult to obtain specific values. As a result, we develop a simple linear model relating distance to cost based on two shipping costs provided by Lockheed Martin for NH_3. The shipping costs are 33 and 72.5 USD per short ton of NH_3 for less than 1000 nautical miles and greater than 10,000 nautical miles, respectively. For CH_3OH production, there is an additional shipping cost for delivering coal to the platform.

Table 1
Capital cost per MW installed and overall efficiency of the synthesizing equipment in kWh/metric ton of product at 50–90% efficiency for the hydrolysis of H_2 [5,16].

Product	Cost (in USD/MW)	Efficiency (in kWh/metric ton of product)
NH_3	1,240	9,800–15,100
CH_3OH	1,800	6,370–10,090
LH_2	1,330	63,500–93,040

Since we are using simplified estimates, we conduct a sensitivity analysis on the shipping costs for the various products. The cost of shipping will depend on the location of the OTEC platform and the destination port. We consider two possible locations for the OTEC platform, the West Atlantic and the West Pacific, with shipments to six potential US ports (Seattle, WA; San Francisco, CA; Tampa, FL; Houston, TX; New Orleans, LA; Wilmington, NC) as well as Guangzhou, China. We calculate the distance between the OTEC platform and the port using an online tool available at www.searates.com [23]. For NH_3 and CH_3OH, we ship to ports with existing infrastructure for that fuel. In Supplementary Data (Section S2), we show the distances from the OTEC platform to port and the availability of port infrastructure. By contrast, H_2 is not sold on a commodity market. Most H_2 is produced in captive (~86%) or merchant (~14%) plants and used in steam reforming of hydrocarbons [24]. Thus, we evaluate a range of potential shipping distances for H_2. Here, we evaluate selling the products directly into the existing markets, and as a result, we consider the presence of infrastructure at the port as sufficient for onshore conversion.

2.2.3. Market prices

We compare the cost of the products from the OTEC platform delivered to market to prices in existing markets in the US and China as well as techno-economic estimates for onshore production processes. We show market and techno-economic prices for NH_3, H_2 and CH_3OH in Supplementary Data (Section S3). NH_3 and CH_3OH are large and liquid markets. Global and regional prices are found in market reports [25,26]. Since H_2 is not available in the market, we investigate a range of prices derived from techno-economic studies compiled in Refs. [27] and [28].

2.3. Environmental characteristics

Finally, we investigate the effect of the environmental characteristics, specifically the damages associated with CO_2, on the cost of delivering the products as well as the market prices. For each step of the pathway, there are externalities (e.g. effects that occur as a part of the process that cause damages to society, but where the costs are not borne by the producer). Identifying and quantifying the cost of these externalities is critical as their presence is an important justification for regulation. An economically efficient regulation would exactly internalize these costs. We compile emission factors for the product from the OTEC platform, shipping by ocean tanker and the existing onshore production processes from Argonne National Laboratory's GREET (The Greenhouse Gases, Regulated Emission and Energy Use in Transportation) model [29]. For the conventional onshore production, there can be a range of different production techniques. We bound our results by comparing a natural gas and a coal production facility for all three energy carriers. We consider only the emissions during the generation phase and do not consider emissions from the feedstock. We show our emission factors and more details on the production techniques in Supplementary Data (Section S4). We monetize the CO_2 emissions using the global social cost of carbon (SCC) estimate from the US government [10]. For 2015, the central estimate is 38 USD/metric ton with a range of 12 USD/metric ton to 109 USD/metric ton. We conduct a sensitivity analysis showing how the costs, efficiencies and CO_2 prices influence the viability of the product.

We assume that CO_2 damages will dominate the social costs. We do not include other greenhouse gases (GHG) due to uncertainty regarding the social damages. We also do not monetize the air quality emissions that lead to adverse human health effects. While these costs could be large, monetizing these damages requires more site specific information than is available in our analysis. Other impacts of OTEC platform may include eutrophication, ecotoxicity and changes in the ocean water characteristics [3]. We address these effects as regulatory issues rather than include them in the monetization.

3. Calculations

Our model starts with the assumption that the OTEC platform is a price taker. In a competitive market, a price taker controls a small portion of the market and therefore cannot influence the market price. Thus, for the products from the OTEC platform, the difference between the market price and the variable cost of production can then be used to recover the capital and fixed costs of the OTEC platform and the onboard product synthesis equipment. For each product, we calculate the difference using Equation (1).

$$a = P - \mathrm{VC} \tag{1}$$

where

a is the differential between the market price and variable cost (in USD/metric ton of product);
P is the price in the market (in USD/metric ton of product); and,
VC is the variable cost of delivery to market (in USD/metric ton of product).

We then compare this difference per metric ton of product to the levelized annualized capital and fixed costs (LAC) for the OTEC platform and the onboard synthesis of the product, expressed in USD/metric ton of product. We show the calculation of the LAC in Equation (2).

$$\mathrm{LAC} = \frac{\left(\mathrm{CC}^{\mathrm{OTEC}} + \mathrm{CC}^{\mathrm{SYN}}\right)\cdot \mathrm{CRF}\cdot \mathrm{EFF}}{\mathrm{HY}} + \frac{\left(\mathrm{FC}^{\mathrm{OTEC}} + \mathrm{FC}^{\mathrm{SYN}}\right)\cdot \mathrm{EFF}}{\mathrm{HY}} \tag{2}$$

where

LAC is the levelized annualized capital and fixed costs (in USD/metric ton of product);
$\mathrm{CC}^{\mathrm{OTEC}}$ is the capital cost of the OTEC platform (in USD/kW);
$\mathrm{CC}^{\mathrm{SYN}}$ is the capital cost of the onboard synthesis equipment (in USD/kW);
CRF is the capital recovery factor;
EFF is the efficiency of the onboard synthesis (in kWh/metric ton);
$\mathrm{FC}^{\mathrm{OTEC}}$ is the annual fixed cost of the OTEC platform (in USD/kW-year);
$\mathrm{FC}^{\mathrm{SYN}}$ is the annual fixed cost of the onboard synthesis (in USD/kW-year); and,
HY is the number of hours of operation per year.

The capital recovery factor (CRF) is employed to annualize the capital costs. It is a function of the discount rate and the number of years of operation for the OTEC platform. As the number of years of operation becomes large, the capital recovery factor converges to the discount rate. We investigate discount rates of 3–10%. We assume a 92% operating capacity to set the number of hours of operation per year.

4. Results and discussion

In Fig. 1, we show the market and techno-economic prices per metric ton and compare them to the variable costs of production and transportation to market. We find that on a per ton basis all energy carriers have lower variable costs than the market prices. Assuming that this difference persists, it can be used to recover the capital costs of the OTEC platform and the onboard synthesis equipment. We assume that the variable costs are dominated by the shipping costs. There may be additional onshore delivery costs at the terminals that have not been included in our variable costs. Thus, our estimate should be interpreted as a best-case scenario.

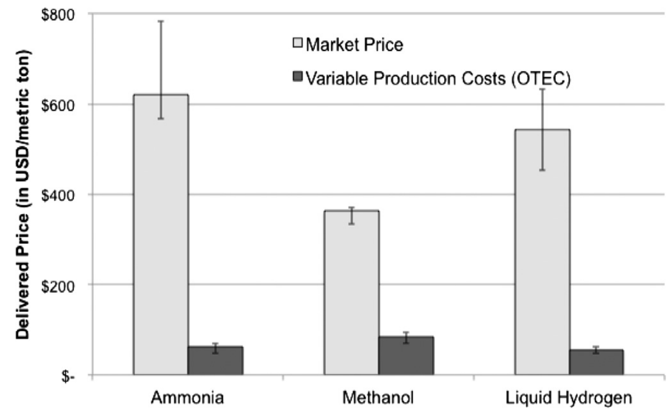

Fig. 1. Comparison of the variable cost of production using the OTEC platform to the market prices in USD/metric ton at delivery for NH_3, LH_2 and CH_3OH. The bars on the market price show the high and low prices for 2010–2012 over six locations. The bars on the variable cost of production show the high and low values for the different transportation distances.

In Fig. 2, we show our estimates for the cost of electricity production from an OTEC platform as a function of discount rate, location and size of the installation. Facilities located in the West Pacific are more favorable than those in the West Atlantic due to the better quality of the thermal resource. The size of the gross facility required for the same net production capacity is larger in the Atlantic, leading to a higher cost. Economies of scale in the production of the components for OTEC platforms also play an important role in the cost estimates. A facility with a 400 MW net capacity is approximately half of the cost per MW-installed of a facility with a 100 MW net capacity. Finally, the discount rate can change the cost by slightly more than 50%. Under the most favorable assumptions, the cost of producing electricity from the OTEC platform approaches the same range as other renewable energy technologies [30].

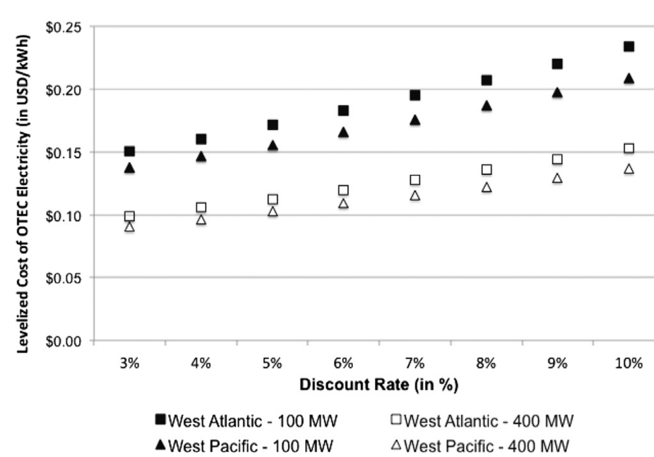

Fig. 2. Levelized annualized costs of electricity production from an OTEC platform in USD/kWh as a function of discount rate, location and size using first of a kind cost estimates.

In Fig. 3a–c, we compare the LAC of the OTEC platform and the onboard product synthesis to the price difference without and with the monetized damages from CO_2 on the basis of a metric ton of delivered product for NH_3, LH_2 and CH_3OH, respectively. We show all capital and fixed costs for a 400 MW OTEC platform located in the West Pacific, representing a best-case scenario. In each figure, we also show the sensitivity of our estimates to the efficiency of the conversion process, the range of market prices, the type of process used for the onshore product, and the damage value of CO_2. Using the USD per metric ton basis allows us to investigate the potential for sales directly into their specific markets, such as NH_3 into the fertilizer market. We also show the same figures on the basis of the energy delivered in mmBTU in Supplementary Data (Section S5). The energy content basis is a more relevant comparison to evaluate markets with near-term potential such as converting the NH_3 or H_2 into electricity or larger transformations such as alternative vehicle fuels.

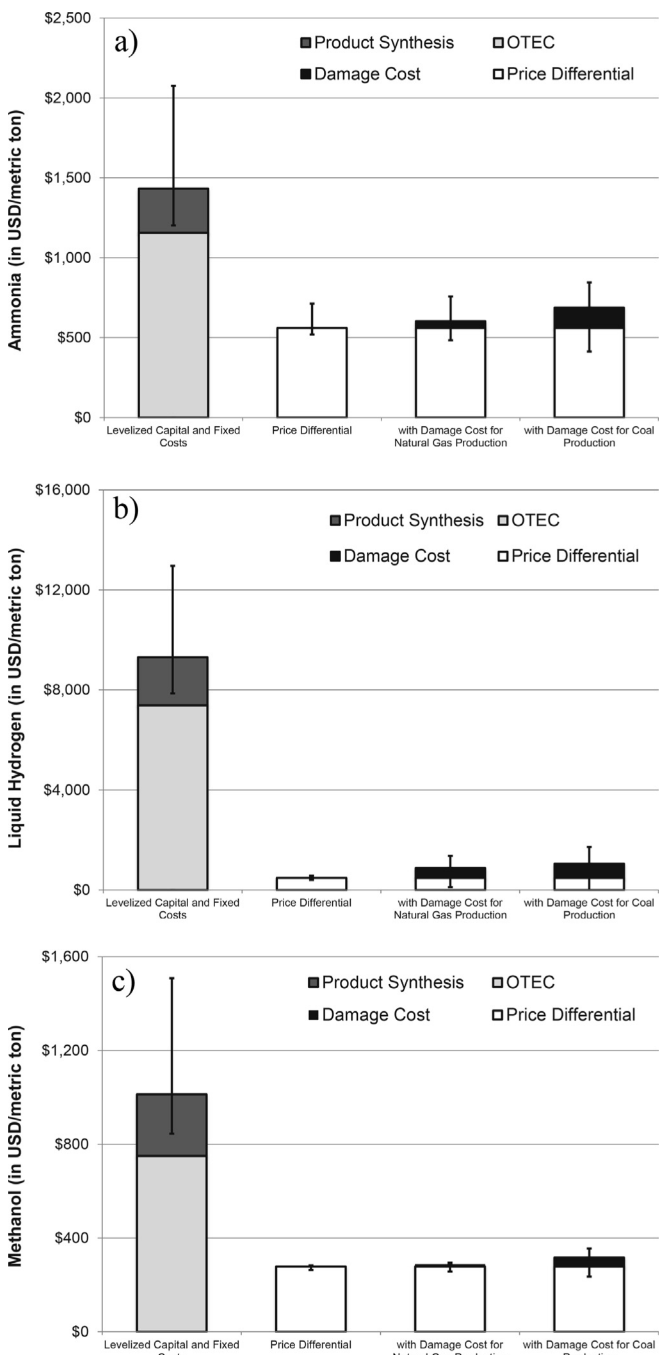

Fig. 3. Comparison of levelized annualized capital and fixed costs (LAC) and price differential for a) NH_3 in USD/metric ton, b) Liquefied H_2 in USD/metric ton and c) CH_3OH in USD/metric ton. The capital and fixed costs are for a 400 MW OTEC platform located in the West Pacific using a discount rate of 4%. The error bars for the capital and fixed cost represent 50–90% efficiency for the onboard synthesis. The error bars on the price differential represent the range of prices in the markets. The error bars on the CO_2 damage costs represent the low and high damages values of 12 USD/metric ton and 109 USD/metric ton (2015).

With the current market prices, we find that the price differential is insufficient to recover the capital and fixed costs of a first of a kind OTEC platform. The NH_3 product performs the best recovering 40% of the costs with a process efficiency of 75% (HHV) for the synthesis equipment and the median NH_3 market price. By contrast, we recover 5% and 27% of the capital and fixed costs for LH_2 and CH_3OH, respectively. It is anticipated that the *n*th unit brought on line will have lower capital costs based on expectations of improvements from "learning-by-doing" as well as technological progress [20]. For a 25% reduction in the capital and fixed costs of the OTEC platform and synthesis equipment, we calculate a recovery of approximately 50% of the capital costs for a NH_3 product, assuming that the market prices do not change. This emphasizes the importance of continuing to reduce the capital cost of the OTEC platform and synthesis equipment.

For NH_3, the market prices are set by the dominant production techniques and are not anticipated to increase in the US. In the US, approximately 98% of NH_3 is produced by catalytic steam reforming of natural gas. The market price is strongly correlated with natural gas prices [31], and natural gas prices are anticipated to remain low in the short-term due to the availability of shale gas. By contrast, China produces over 60% of its NH_3 from coal gasification, which is more expensive than steam reforming at lower natural gas prices [26]. There do not appear to be immediate opportunities to sell LH_2 and CH_3OH at existing market prices.

While the OTEC platform provides CO_2-free electricity, transportation and delivery to market involves emissions. The onshore production processes also involve CO_2 emissions with higher emissions from coal than natural gas. Applying a cost on these emissions equivalent to the social damage to both the product from the OTEC platform and the onshore processes adds a small premium to the onshore process. This increases the price differential for the product from the OTEC platform. However, the entire cost of the OTEC platform and synthesis process, at least with the current capital costs and efficiency, cannot be recovered even at the higher range of social costs. CO_2 social damages would need to be approximately three times greater than the high range value of 109 USD/metric ton [10]. There are other externalities for both the OTEC platform and the onshore processes that have not been monetized in this analysis. First, there are other emissions with climate forcing properties, such as other GHGs and particulate matter. The social cost estimates, however, are highly uncertain. Evaluating the net climate forcing properties of particulates is also complex since some components warm and others cool [32]. Second, we have not considered the adverse health effects related to particulate matter and other emissions. Previous analysis has attributed approximately 60,000 annual premature deaths from cardiovascular disease and lung cancer to shipping emissions [33]. The fraction of these deaths that would be attributed to our tankers is likely very small. Additional concerns may arise from water withdrawals and potential ecosystem impacts [3]. Monetizing these externalities would require more site-specific information. In addition to the non-monetized externalities, there are also possible regulatory concerns that may affect grazing OTEC platforms. Presently, the National Oceanic and Atmospheric Administration (NOAA)'s Office of Ocean and Coastal Resource Management is renewing the licensing requirements for commercial OTEC facilities

[34]. However, since there are no existing OTEC platforms, we cannot evaluate the costs of meeting regulatory requirements.

In this analysis, we focus on the delivery of products from the OTEC platform into existing markets for NH_3 and CH_3OH. For H_2, the product from the OTEC platform would likely be sold under contract for an existing user. In the longer term, we can envisage a number of additional products from an OTEC platform. For example, NH_3 and H_2 could be transformed into electricity onshore through combustion or fuel cells. Prevailing electricity prices and the cost of the fuel cells as well as the availability of natural gas for combustion turbines do not make this pathway cost-effective at this time [35]. This pathway, however, could be important in a system that incorporates increasing amounts of renewables, where NH_3 or H_2 could be employed as storage to manage the intermittency of wind and solar power [36]. The energy carriers explored in this work could also be used as part of larger transformations, such as providing H_2 for the expanded use of fuel cells for electricity and transportation [37]. We also recognize that the OTEC platform could be used for other purposes than electricity generation, like the multifunction platform under development by the European Union's TROPOS project [38].

5. Conclusions

Here, we conduct an analysis of the economic and environmental effects of the synthesis, transportation and delivery to market of three bulk energy carriers from a grazing OTEC platform. We screen a wide range of possible carriers across the costs, technological maturity, existing and near-term market size and product prices. We identify NH_3, CH_3OH and LH_2 as the most promising options. For all three products, we find that the variable production costs are lower than the price in current onshore markets since the electricity from the OTEC platform has negligible variable operating costs. The differential, however, is insufficient to recover the capital and fixed cost of a first of a kind OTEC platform and onboard synthesis equipment. NH_3 performs best with approximately 40% recovery of the capital and fixed costs.

We examine reductions in the capital costs for the grazing OTEC platform and synthesis equipment, improvements in the efficiency of the synthesis equipment, and increases in the damages associated with CO_2. We note that our cost estimates are for the first of kind grazing OTEC platform, and capital costs should improve with installed capacity. A reduction of 25% in the capital costs, consistent with a 3% per year reduction over 10 years, is not sufficient by itself for the complete recovery of the capital costs. Similarly, synthesis efficiencies of greater than 90% for the electrolysis of H_2 do not cover the capital costs. Finally, under policies that aim to reduce CO_2 emissions, renewable resources that produce energy without generating CO_2 and other GHG emissions will be increasingly valuable [39]. We find that the CO_2 emissions from shipping are lower than the existing onshore production methods that use either natural gas or coal. However, we find that CO_2 costs would need to exceed three times the damage estimates presently used by the US government to recover the capital costs of the OTEC platform and synthesis equipment. Therefore, we recommend a focus on substantially reducing the capital costs of both the OTEC platform and onboard synthesis equipment to enhance the viability of grazing OTEC platforms supported by long distance bulk energy transport.

Acknowledgments

The authors acknowledge funding from Lockheed Martin and specifically the assistance of Robert Varley, Vincent M. Dothard and Laurie E. Meyer. We also thank Michael Frame for coordinating this effort.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2014.05.021.

References

[1] Office of Technology Assessment. Renewable ocean energy sources. Part 1: ocean thermal energy conversion. Congress of the United States; 1978.
[2] Huang JC, Krock HJ, Oney SK. Revisit ocean thermal energy conversion system. Mitig Adapt Strat Gl 2003;8:157–75.
[3] Comfort CM, Vega L. Environmental assessment for ocean thermal energy conversion in Hawaii: available data and a protocol for baseline monitoring. In: OCEANS 2011; 2011. pp. 1–8.
[4] Nihous GC. An estimate of Atlantic Ocean thermal energy conversion (OTEC) resources. Ocean Eng 2007;34:2210–21.
[5] Avery WH, Richards D, Dugger GL. Hydrogen generation by OTEC electrolysis, and economical energy transfer to world markets via ammonia and methanol. Int J Hydrogen Energy 1985;10:693–702.
[6] Konopka AJ, Talib A, Yudow B, Biederman N. Optimization study of OTEC delivery systems based on chemical-energy carriers. Institute of Gas Technology; 1977. ERA Report No. NSF-C1008.
[7] Cavrot DE. Economics of ocean thermal energy conversion (OTEC). Renew Energy 1993;3:891–6.
[8] Van Ryzin J, Grandelli P, Lipp D, Argall R. The hydrogen economy of 2050: OTEC driven?. In: OCEANS, 2005. Proceedings of MTS/IEEE; 2005. pp. 2675–82.
[9] Avery WH, Wu C. Renewable energy from the ocean: a guide to OTEC. USA: Oxford University Press; 1994.
[10] Interagency Working Group on the Social Cost of Carbon. Technical support document: technical update of the social cost of carbon for regulatory impact analysis – under executive order 12866 http://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf; 2013.
[11] Knoepfel IH. A framework for environmental impact assessment of long-distance energy transport systems. Energy 1996;21:693–702.
[12] Bergerson JA, Lave LB. Should we transport coal, gas, or electricity: cost, efficiency, and environmental implications. Environ Sci Technol 2005;39:5905–10.
[13] Oudalov A, Lave LB, Reza M, Bahrman MP. A method for a comparison of bulk energy transport systems. Environ Sci Technol 2009;43:7619–25.
[14] Morgan MG, Henrion M, Mitchell S. Analytica: a software tool for uncertainty analysis and model communication. In: Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge, MA: University Press; 1990. pp. 257–90.
[15] Lumina Decision Systems Inc.. User guide: Analytica 4.4 www.lumina.com/support/downloads/; 2012.
[16] Lockheed Martin Mission Systems and Sensors. Ocean thermal energy conversion life cycle cost assessment: final technical report. Award # DE-EE0002663; 2012.
[17] Zegers P. Fuel cell commercialization: the key to a hydrogen economy. J Power Sources 2006;154:497–502.
[18] Chang CD, Kuo JCW, Lang WH, Jacob SM, Wise JJ, Silvestri AJ. Process studies on the conversion of methanol to gasoline. Ind Eng Chem Process Des Dev 1978;17:225–60.
[19] Olah GA. Beyond oil and gas: the methanol economy. Angew Chem Int Ed 2005;44:2636–9.
[20] Nagy B, Farmer JD, Bui QM, Trancik JE. Statistical basis for predicting technological progress. PLoS One 2013;8:e52669.
[21] US Bureau of Labor Statistics (BLS). Producer price index for chemical and allied products (PPI-CAP) www.bls.gov; 2012.
[22] Dothard V. Personal communication from Lockheed Martin; 2012.
[23] Sea-Rates.com, www.searates.com, last visited: November 4, 2012
[24] Gainer K. Market research report – hydrogen as a chemical constituent and as an energy source. Wellesley, MA: BCC Research; 2011.
[25] CMAI (IHS). Methanol market report; 2011.
[26] CRU. Ammonia prices www.crugroup.com; 2012.
[27] Energy Efficiency and Renewable Energy. Hydrogen production costs. US Department of Energy; 2012. http://www1.eere.energy.gov/vehiclesandfuels/facts/favorites/fcvt_fotw205.html.
[28] Adamson KA, Pearson P. Hydrogen and methanol: a comparison of safety, economics, efficiencies and emissions. J Power Sources 2000;86:548–55.
[29] Argonne National Laboratory. GREET: the greenhouse gases, regulated emission and energy use in transportation model http://greet.es.anl.gov; 2012.
[30] Roth IF, Ambs LL. Incorporating externalities into a full cost approach to electric power generation life-cycle costing. Energy 2004;29:2125–44.
[31] Huang W. Impact of rising natural gas prices on US ammonia supply. A Report from the Economic Research Service. US Department of Agriculture; 2007., http://www.ers.usda.gov/media/198815/wrs0702_1_.pdf.
[32] Lauer A, Eyring V, Corbett JJ, Wang C, Winebrake JJ. Assessment of near-future policy instruments for oceangoing shipping: impact on atmospheric aerosol burdens and the earth's radiation budget. Environ Sci Technol 2009;43:5592–8.

[33] Corbett JJ, Winebrake JJ, Green EH, Kasibhatla P, Eyring V, Lauer A. Mortality from ship emissions: a global assessment. Environ Sci Technol 2007;41:8512–8.
[34] Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration. Ocean thermal energy conversion: assessing potential physical, chemical and biological impacts and risks http://coastalmanagement.noaa.gov/otec/docs/otecjun10wkshp.pdf; 2010.
[35] US Energy Information Administration (EIA). Electricity data – average retail price of electricity to ultimate consumers – by sector and by state www.eia.gov/electricity/data.cfm; 2012.
[36] Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs, and policies. Energy Policy 2011;39:1170–90.
[37] Colella WG, Jacobson MZ, Golden DM. Switching to a US hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and greenhouse gases. J Power Sources 2005;150:150–81.
[38] TROPOS project, http://www.troposplatform.eu/, visited on March 5, 2013
[39] Pacala S, Socolow R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 2004;305:968–72.