Technology White Paper

on

Generation of Hydrogen and Transportation and Transmission of Energy Generated on the U.S. Outer Continental Shelf to Onshore

Minerals Management Service
Renewable Energy and Alternate Use Program
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INTRODUCTION

With the passage of the Energy Policy Act of 2005 (EPAct), Public Law 109-58 (H.R. 6), the Minerals Management Service (MMS), a bureau of the U.S. Department of the Interior, was given jurisdiction over Renewable Energy and Alternate Use Program projects, such as wind, wave, ocean current, solar energy, hydrogen generation, and projects that make alternative use of existing oil and natural gas platforms in Federal waters. A new program within MMS has been established to oversee these operations on the U.S. Outer Continental Shelf (OCS). MMS is developing rules to guide the application and permitting process for development of Renewable Energy and Alternate Use Program projects on the OCS. To apply the requirements of the National Environmental Policy Act (NEPA) in the establishment of national offshore alternate energy development policy and a national alternate-energy-related use program and rules, MMS plans to prepare a programmatic environmental impact statement (Programmatic EIS). The Programmatic EIS process will (1) provide for public input concerning the scope of national issues associated with offshore alternate-energy-related use activities; (2) identify, define, and assess generic environmental, sociocultural, and economic impacts associated with offshore alternate-energy-related use activities; (3) evaluate and establish effective mitigation measures and best management practices to avoid, minimize, or compensate for potential impacts; and (4) facilitate future preparation of site-specific NEPA documents—subsequent NEPA documents prepared for site-specific Renewable Energy and Alternate Use Program projects will tier off of the Programmatic EIS and Record of Decision. The Programmatic EIS will evaluate the issues associated with development, including all foreseeable potential monitoring, testing, commercial development, operations, and decommissioning activities in Federal waters on the OCS. Information defining the issues and current technology will be obtained primarily from Federal research organizations, MMS, industry, and other valid sources.

In preparation for the Programmatic EIS, MMS has developed a series of White Papers on topics of interest to the Renewable Energy and Alternate Use Program. The overall objective of the White Papers is to provide sufficient information on the prospective alternative technologies to support assessments of the potential environmental impacts of the technologies and of the viable impact mitigation strategies in the Programmatic EIS. The White Papers also will serve as sources of information for stakeholder outreach.

This paper discusses the transportation of energy generated on the U.S. OCS to onshore. The options considered are (1) the generation of hydrogen offshore and transportation of hydrogen onshore and (2) the transport of electricity.[1] Companion papers in the series address the generation of energy on the OCS from wind, waves, solar radiation, and ocean currents.

[1] Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not represent its endorsement, recommendation, or favoring by MMS, the United States government, or any agency thereof.

CONSIDERATIONS FOR HYDROGEN AS AN ENERGY RESERVE

For the alternative energy sources under consideration, energy is not always produced when it is needed. To address the sporadic and sometimes unpredictable nature of energy production from these sources, methods for the interim storage of excess alternative energy must be developed. One currently proposed approach is the use of hydrogen (H_2) produced in OCS alternative energy facilities. Hydrogen can be generated on location on a variety of scales; it can then be compressed and stored in tanks, transported in tanks or pipelines, and later consumed by vehicles for power or by industrial facilities or generating stations to produce process steam or provide electricity. No serious proposals have yet been made to use other energy storage technologies, such as batteries, flywheels, superconducting magnetic energy, compressed air, pumped hydropower, and supercapacitors, with OCS alternative energy facilities on the scale of a small power generation facility in a marine environment.

If hydrogen is to be used as a means of energy storage for potential OCS energy generation, options for the locations and designs of the conversion facilities must be considered. For example, hydrogen could be produced offshore at the point of energy generation in a co-located facility, or it could be produced at an onshore location near the offshore power generation facility. Any final design would have to take into account the general location and type of the alternative energy source and the location of the area for which it is providing energy.

Hydrogen production at a co-located facility would require additional construction in a marine environment and equipment capable of long-term function in an offshore setting. Routine servicing of the hydrogen generation plant would require personnel travel and work in the marine environment. Additionally, if multiple power generation units were involved (such as the individual turbines found on a wind energy facility), a hydrogen production unit could be associated with each turbine or with the entire facility. In the former case, consolidation of the hydrogen would be necessary for shipment off-site; in the latter case, electrical connections between the individual turbines and the hydrogen production unit would be required.

Hydrogen production at a nearby onshore location would offer particular advantages when operated in conjunction with OCS energy sources already connected to a land-based electric power grid. In such systems, electricity from OCS sources could be diverted for use in hydrogen production when available energy on the grid from conventional sources was sufficient to meet existing power demands.

HYDROGEN GENERATION

The alternative energy sources under consideration for the OCS (i.e., wind, wave, ocean current, and solar) involve processes that directly produce electricity. If this energy is to be stored, the electricity can be used to produce hydrogen. This conversion can be accomplished using electrolysis. For solar power, electricity may be generated with the use of a photovoltaic cell, but hydrogen may also be generated directly through one of two photolytic processes.

Electrolysis

Electrolysis is the process of producing hydrogen and oxygen from water in an electrochemical cell. Two types of electrochemical methods, alkaline or proton exchange membrane (PEM), are used in commercially available equipment commonly referred to as electrolyzers (Ivy 2004). An alkaline electrolyzer immerses the two electrodes, the cathode and the anode, into an aqueous alkaline electrolyte, typically a solution of sodium or potassium hydroxide, and a voltage is applied across the electrodes. The resulting migration of ions in solution results in the production of hydrogen at the cathode and oxygen at the anode according to:

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \qquad \text{Cathode reaction}$$
$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \qquad \text{Anode reaction}$$

In a PEM electrolyzer, the mobile ion is a proton in an electrolyte that is a proton-conducting polymer membrane. The reactions at the electrodes in this case are:

$$4H^+ + 4e^- \rightarrow 2H_2 \qquad \text{Cathode reaction}$$
$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad \text{Anode reaction}$$

Currently, the best conversion efficiency (i.e., overall system efficiency for converting electrical power to power stored as hydrogen) for commercial electrolyzers is approximately 70% (Ivy 2004; DOE 2005a).

Solid oxide electrolyzers are currently under development. This method uses a solid ceramic material as the electrolyte that allows the transmission of negatively charged oxygen ions at elevated temperatures. Water at the cathode reacts with electrons to form hydrogen gas and negatively charged oxygen ions. The oxygen ions migrate through the electrolyte to the anode where they react to form oxygen gas and give up electrons. Operation occurs at temperatures (500 to 800°C) conducive to oxygen ion migration in the ceramic electrolyte. Operation at these elevated temperatures reduces the amount of electrical energy required to produce hydrogen from water. However, a heat source is needed, making this option more attractive in combination with an energy source that is capable of producing large amounts of heat.

Photolytic Methods

Solar energy can be used to convert water to hydrogen and oxygen directly; electricity need not be first generated with a photovoltaic cell. This conversion can be accomplished by using either photoelectrochemical or photobiological methods.

A particular type of photoelectrochemical cell can directly dissociate water into hydrogen and water using specialized semiconductor materials at one or both electrodes (Lewis 2001). Different electrode materials work at different wavelengths of light. Research to identify water-stable semiconductor materials that have the highest efficiency in the solar spectrum is ongoing.

Photobiological methods rely on the production of hydrogen by certain types of algae and bacteria (Melis and Happe 2004; Akkerman et al. 2002). Analogous to plants that produce oxygen from water as a by-product of their metabolism, these microorganisms produce hydrogen. Although this process is presently too slow to harness for use with offshore solar energy collection, researchers are investigating ways to enable this process to become an important piece in sustainable hydrogen production with low environmental impact.

TRANSPORTATION OF HYDROGEN FROM THE OCS TO ONSHORE

Offshore-generated hydrogen could be delivered to onshore facilities by several means. The three that have the highest potential are:

1. Transport as gaseous hydrogen,

2. Transport as liquid hydrogen, and

3. Transport after incorporation into a solid or liquid “hydrogen carrier.”

In the first two pathways, hydrogen would be transferred from the OCS to shoreline facilities as pure hydrogen in its molecular form (H_2), either as compressed gas or as liquid, via pipeline, tanker, or a ship. The carrier path would use materials that would transport hydrogen in a form other than free H_2 molecules. These materials would include liquid hydrocarbons, absorbents, metal hydrides, and other hydrogen-rich compounds.

Transport as Gaseous Hydrogen

For economic reasons, H_2 would need to be compressed to be transported ashore in gaseous form. The actual transport could be through a pipeline that runs between a generating facility on the OCS and an onshore receiving facility. After arriving on land, the hydrogen would need to be connected to the onshore distribution and delivery system. This paper assumes that such a distribution and delivery system exists. The focus of this paper is limited to delivery of OCS-produced hydrogen to the facilities on the shoreline.

Pipelines have been used extensively in the United States and elsewhere to transport natural gas and crude oil. Currently, approximately 1,000 km of dedicated hydrogen transmission pipelines exist in the U.S. (DOE 2005b). Some of these hydrogen pipelines were built expressly for hydrogen delivery, while others were previously used for natural gas or crude oil transmission. In addition, there are also pipelines that transport oil from offshore production facilities to the shore. Therefore, it is foreseeable that pipelines for transmission of hydrogen from an offshore alternative energy facility to an onshore point of delivery could be constructed.

There are some technical concerns with hydrogen transport that do not exist with natural gas or oil. The primary concern is the potential for hydrogen to embrittle the steel and the welds used to fabricate the pipelines. Other potential obstacles include the need for improved seal technology and techniques to control permeation and leakage in general. Because of hydrogen's low molecular weight, leakage from equipment is difficult to control. At the same time, hydrogen, particularly high-pressure hydrogen, presents special safety concerns. The relatively low activation energy required for hydrogen ignition and the broad range of hydrogen concentrations in air that can be explosive mandate extremely low equipment leakage. Although these concerns are common to both offshore and onshore equipment, the explosion hazard is relevant only in confined air spaces. While these problems are not insurmountable, they add to the cost of generation, storage, delivery, and use of hydrogen. Research is ongoing to find cheaper and more flexible options for the handling of hydrogen.

Compressed hydrogen can also be transported to shore in pressurized containers loaded on a ship or in specially designed tankers. The United States has considerable industry experience in handling and transporting pressurized gas cylinders; the shipment of high-pressure hydrogen cylinders is now commonplace. Once the specific concerns about the handling and leakage of hydrogen are addressed, the remaining issue is one of economics.

Transport as Liquid Hydrogen

The transportation of hydrogen as a liquid in molecular form requires liquefaction, which is a well-understood but costly operation. The liquefaction process involves cooling gaseous hydrogen to below −253°C using liquid nitrogen and a series of compression and expansion steps (FCFP 2005), a very energy-intensive process. With current technologies, this process can consume one-third or more of the energy contained in the hydrogen (FCFP 2005). Once liquefied, hydrogen would need to be stored and transported at cryogenic temperatures until it is ready to be vaporized to a high-pressure gaseous form for dispensing. These requirements would rule out the use of pipelines for transport from the OCS to the shore. Therefore, the only practical pathway would be via ship or tanker.

Transport after Incorporation into a Hydrogen Carrier

A hydrogen carrier is any substance that can be used to store and transport hydrogen in a chemical state other than as free diatomic hydrogen molecules (i.e., H_2). An effective potential carrier would have the following characteristics (FCFP 2005):

- Operate at reasonable temperatures and pressures;
- Provide high hydrogen capacity per unit volume or mass;
- Allow for the safe and relatively simple addition or removal of hydrogen at low cost and high efficiency; and
- Be safe and environmentally benign.

A one- or two-way carrier could be employed. In a one-way carrier, hydrogen is added to the carrier at the point of initial charge and remains with the carrier until it reaches its point of use. At the point of use, the carrier/hydrogen combination is decomposed to yield hydrogen and an environmentally benign substance with no economic value. Hydrogen is used, and the remaining by-product is lost to the environment. An example of a one-way carrier would be ammonia (DOE 2006). The by-product material would be nitrogen.

In a two-way system, the carrier would be charged with hydrogen at an OCS hydrogen generation station and transported to the shore. On shore, the carrier would be stripped of its hydrogen and sent back offshore for recharging. Whether the carrier is one-way or two-way, it could be transported between the offshore generating station and an onshore facility by pipeline (if it is in a liquid or slurry state) or by ship or tanker. Potential two-way carriers include metal hydrides and liquid hydrocarbons. A considerable amount of research has been conducted in the United States and abroad on hydrogen carriers, but no commercial-scale methods have yet been developed.

TRANSMISSION OF ELECTRICITY FROM THE OCS TO ONSHORE

Direct transmission of electricity from offshore locations is more straightforward and more energy efficient than the use of hydrogen as an intermediate stage, but demand is not always concurrent with supply. Transmission of electricity from an alternative energy source on the OCS to an onshore location would likely require a submarine cable. Submarine cables are used to provide power to island communities and are also used extensively in offshore oil and gas exploration to provide power, communication, and control lines to offshore platforms. Submarine cable technology is already used to provide electricity from offshore wind facilities to onshore electric power substations in Europe.

High-voltage alternating-current (AC) electric transmission lines are typically used, but transmission distances are generally on the order of a few kilometers. Because the economic limit on high-voltage AC transmission is estimated to be between approximately 30 and 250 km (Wright et al. 2002), the use of high-voltage AC transmission lines would be problematic for offshore energy generation locations farther from land. Transmission of AC power suffers from losses due to capacitance and other factors, such as induced current in the shielding, that are not present with direct-current (DC) power transmission.

With the same size cable, DC transmission lines can carry more power than AC lines and require fewer conductors. Also, the AC voltage at either end of the DC cable can be different, possibly eliminating the use of a transformer, and the direction and magnitude of the power flow can be controlled. The limiting factors for the use of high-voltage DC (HVDC) tend to be cable cost, laying cost, and manufacturability rather than distance (Wright et al. 2002). One of the larger impediments to the use of HVDC has been the lack of power electronics to convert between voltage levels (DC-to-DC) as is accomplished through the use of step-up and step-down transformers in AC power systems. New, commercialized HVDC converter technology may make HVDC an even more attractive option as there are already a number of HVDC submarine power cables in use.

While some alternative energy sources are better suited to AC power generation (i.e., wind, ocean current, or wave) and others (i.e., solar) are better suited to DC power generation, interconversion between AC and DC power is a relatively mature technology. The driving factor for the selection of AC or DC transmission to onshore facilities might be expected to depend on costs.

ENVIRONMENTAL CONSIDERATIONS

Environmental impacts that would need to be considered in evaluating the options for transmission of energy generated at the OCS facilities to shore would include construction and operation impacts associated with activities such as submarine cable installation and use, hydrogen generation facility construction and use, and hydrogen transport.

Hydrogen Generation

The co-location of hydrogen generation and potential storage offshore with an alternative energy source would increase the disturbed area in the marine environment. Such a disturbance would be similar to that posed by an offshore oil platform (e.g., support pillars extending from a platform into the seafloor). However, the primary source material, water, and the primary by-product, oxygen, of hydrogen generation from electrolysis are environmentally friendly. In the case of an offshore operation, seawater would be preprocessed (i.e., desalinized) before use in the electrolyzer. Precautions would need to be taken to minimize any leaks or spills of hazardous material (e.g., gasoline or oil) associated with maintenance craft and routine facility operation or repair of equipment. Maintenance of the water purification and electrolysis equipment would pose typical industrial physical and mechanical hazards. Additional safeguards related to hydrogen handling would be required to mitigate hazards associated with its explosive nature and compressed gases or cryogenic liquids.

Hydrogen Transport

Hydrogen generated at offshore locations would be sent to onshore facilities via pipelines, ships, or tankers. The same hydrogen-specific hazards discussed above for hydrogen generation apply to all transport modes. Care would have to be taken to guard against hydrogen’s flammable nature and leaks and embrittlement of piping and equipment.

The use of a hydrogen pipeline would entail proper design, installation, and operation to minimize environmental impacts. Pipelines may lie on or be buried below the seabed. However, in shallow water, typically 5 m or less, offshore pipelines must be placed below the seabed to avoid exposure to navigation hazards (DOT 2006). Route determination for the pipeline should minimize its length to reduce its impact, but other issues such as sensitive underwater habitats (e.g., shellfish beds), pipeline size, ease of construction, seismic faults, seabed terrain and soil, and physical access for inspection and repairs must also be considered. Design considerations include minimizing the hazards from and to boat anchors and fishing vessel activity, as well as hazards from corrosion and the potential for winter ice in northern areas. Temporary disturbances to marine life would occur during pipeline construction and removal but would be minimal during operation for buried pipelines. Pipelines situated on the seafloor might cause some loss of seafloor habitat but would be installed to minimize migratory and feeding impacts on local marine life.

Environmental impacts associated with ship and tanker transport of H_2 include normal vessel traffic, loading and unloading accidents, and transportation accidents. Impacts from normal vessel traffic would result from air emissions and surface water disturbance due to vessel passage and docking at the offshore facility. Vessel traffic could also result in the inadvertent leakage of waste, gas, or oil to the marine environment. Accidents could result in the explosive release of hydrogen and/or the release of materials such as waste, gas, or oil to the marine environment.

Electricity Transmission

The environmental issues from transmission of electricity from offshore alternative energy sources include many of the same considerations discussed above for buried pipelines, namely: underwater length, disturbance of sensitive underwater habitats, time and area associated with installation, protection against seismic faults, seabed terrain and soil, and physical access for inspection and repairs. An additional concern for electricity transmission would be the potential effects on aquatic organisms resulting from magnetic fields around the cables during operation.

ECONOMIC CONSIDERATIONS

The costs associated with offshore power generation and the transport of electricity alone include the cost of the transmission cable and the components required to interconnect the cable with the energy source on the offshore side and the power grid onshore. As discussed, HVDC transmission lines may become more economically attractive as the transmission distances increase. Additional costs are incurred for the installation of the cable and future maintenance activities.

Generation of electricity by alternative energy sources may not always coincide with demand, resulting in lost energy when demand is less than the power output. However, this excess energy could be stored for later use if a suitable storage method is available. For any storage method to be practical, it must perform reliably and be economically competitive and/or fill a niche market. In the case of H_2 generation and storage, viable processes are available for use. Also, extensive research on implementing a hydrogen economy, primarily in the area of transportation to supplant waning supplies of crude oil, is ongoing. What must be considered is the energy (or substitute H_2 fuel) that may be lost when an alternative energy source provides excess power in periods of low demand. Is it economically realistic to construct and operate an H_2 storage and transport operation in conjunction with an alternative energy source? In other words, would the H_2 generated pay for itself?

Costs associated with the use of H_2 include its generation, storage, and transport. The electrolysis of water to produce H_2 is a commercially proven technology, the cost of which is slowly declining as the conversion efficiency (the amount of H_2 produced per amount of energy input) increases with improvements in electrolyzer design. It should also be recognized that a certain energy loss will occur when H_2 is used as fuel, because no fuel cell is 100% efficient.

Hydrogen storage at the points of generation and use requires an investment in compressed gas vessels, storage tanks, and equipment designed to handle hydrogen's chemical and physical properties and to prevent or mitigate adverse consequences of accidental release. If H_2 is to be stored in liquid form (with an energy density about seven times that of the compressed gas), transportation costs may be reduced, but liquefaction requires a high energy input and additional costs are incurred for cryogenic equipment. The use of H_2 carriers is not yet a viable technology and will require an unknown investment in future research.

The use of pipelines for the transport of H_2 is feasible, but most existing pipelines have been converted from the transport of oil or gas to H_2 and operate at lower pressures. To support a higher throughput volume of H_2, higher pressure operation would be needed, which would entail extra energy for compression of the gas. In addition to the installation, maintenance, and higher material costs for an H_2 pipeline, the availability of the infrastructure on land for distribution and delivery of the H_2 to users must be considered.

A comparative evaluation of the costs of producing and delivering hydrogen on offshore facilities is presented in Altmann and Richert (2001). In this evaluation, hydrogen is produced by offshore electrolysis with the electricity having been generated via wind power. Four options for transporting the hydrogen to an onshore facility are considered: (1) pipeline from the offshore facility to the nearest large city; (2) pipeline to an onshore liquefaction center followed by truck transport of the liquid hydrogen to the city; (3) offshore liquefaction followed by the loading of standard 40-ft-long liquid hydrogen cylinders; and (4) offshore liquefaction followed by the loading of the liquid hydrogen onto large tanks mounted on floating barges. The first option is used as a reference case in this comparative assessment.

From a capital-cost perspective, the second option is approximately 50% more expensive than the reference case. Most of the capital-cost differential is in the onshore liquefaction. The third option is approximately 150% more expensive than the reference case, principally due to the container, the cylinders, the larger offshore platform required, and offshore liquefaction. The barge option is approximately twice that of the reference case, with the capital cost difference primarily due to offshore liquefaction, the larger platform, and the barge. Similar results are observed in the comparison of the cost of the delivered hydrogen. The electrolysis costs are considerably higher in the liquefaction cases because much electrical energy must be generated to operate the liquefaction units.

Conclusions from the above comparisons include: (1) sea transport of liquid hydrogen appears to be significantly more costly than pipeline transport, and (2) the pipeline costs would make only a modest contribution to the cost of delivered hydrogen in this specific application. Significant improvements and cost reductions in the liquefaction technology, and in the storage and transport of liquid hydrogen, would be needed to make these options economically competitive with gaseous hydrogen transport via pipeline.

SUMMARY

Electricity generated by alternative energy sources on the OCS can be brought onshore by using submarine cables that connect to the power grid. Relatively short HVAC cables, on the order of a few kilometers, have been used in past offshore wind facilities. However, distances beyond 50 km may be proposed for future sources on the OCS. At such distances, it may be more practical and economical to use HVDC transmission as newer HVDC converter technology is commercialized.

Because the alternative energy sources do not always produce electricity during periods of demand, the use of H_2 has been suggested as an energy storage medium. Presently, the most practical method for the generation of H_2 from alternative energy sources is the electrolysis of water. (Direct photochemical or photobiological methods of H_2 generation from solar energy, bypassing the initial production of electricity, are under investigation, but these methods are not currently viable on a commercial scale.) The H_2 may then be stored and transported in gaseous form to end-use locations. Hydrogen could be liquefied for storage and transport, but such processing is complex and may not be cost-effective. Hydrogen carriers are under investigation but are not yet commercially feasible. Transport of H_2 would occur in pressure vessels and/or pipelines to the end user.

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