Ocean Thermal Energy for Abatement of Global CO_2 Emissions

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ABSTRACT

The world's oceans are the largest collectors and storage of solar energy and have an enormous potential to supply growing worldwide energy demands, commodity products like ammonia, and fresh water. Global energy, environment, and economic settings have drastically changed: uncertain energy costs; increased energy demands of economic emerging countries; awareness of impact of CO_2 emission; recognition of Energy-Water-Food Nexus to support alternate energy production and growing population. There are global movements of reducing CO_2 emissions. Besides replacing coal with natural gas and CO_2 capture & sequestration (CCS) new technologies are being developed for conversion of CO_2 to value-added products. Ocean Thermal Energy Conversion (OTEC) has potentials of making significant contribution to reduce global CO_2 emissions. With full implementation by 2040, the OTEC technology would play a significant role in the global CO_2 abatement.

Keywords: ocean thermal energy, small island states, ammonia production, methanol production, desalination

1 INTRODUCTION

In the past two centuries, fossil fuel supplied by coal, petroleum and natural gas has played a key role in establishing the modern world economy. When the global demand for electricity increased from 8.3 million GWh (1980) to 22.7 million GWh (2012), the resulting annual CO_2 emission increased from 5.5 to 13.3 billion tonnes [1]. Today, the global demand for energy-intensive products, such as ammonia and plastics, is also expanding with the growing population and improved standards of living in emerging markets. The impact of rising CO_2 levels on climate change is now taken seriously, as demonstrated by the COP21 meeting in Paris, which has stimulated global action to reduce CO_2 emission. Considering the magnitude of the issue, concerted efforts will be required to stabilize and then reduce CO_2 levels in the atmosphere. There are global movements to reduce emission of green-house gases (GHGs) and Ocean Thermal Energy Conversion (OTEC) potentially could make a significant contribution towards reducing the global CO_2 emissions.

The world's oceans are the largest collectors and storage of solar energy and have an enormous potential both to supply growing worldwide energy demands, as well as provide commodity products like ammonia and fresh water. Significant technical progress has been made on OTEC and the major technical barriers have been removed by a multi-year development between 1970's and 1990's. Despite these significant developments, not a single commercial OTEC plant was installed. As a consequence of low fossil energy costs, the OTEC program diminished in early 1990's. Today, global energy, environment, and economic settings have drastically changed: uncertain future energy costs; increased energy demands from emerging economies; awareness of the impacts of green-houses gas (GHG) emissions; and recognition of the "***Energy-Water Nexus***." Water scarcity is being recognized to support production of alternate energy sources, such as fracking for oil and gas production as well as production of biobased fuels. In recent years, commercialization of the OTEC technology is being actively pursued by private organizations with the focus on the island states. The deployment of the first commercial scale OTEC plant is expected to accelerate implementation of the OTEC technology globally. The techno-economic merit of the first generation of OTEC plants must include potential co-production of desalinated water, seawater air conditioning (SWAC) and commodity products, such as ammonia, based on seasonal demand of the baseload power.

2 VISIONARY GOALS

The five-step visionary goals for global implementation of the OTEC technology are:

1. Global displacement of petroleum-based power generation in the island states;
2. Production of ammonia using OTEC plantships to displace coal-based ammonia production;
3. Desalinated water production for regions with critical shortages of potable water
4. Conversion of captured CO_2 from coastal utility and industry plants to methanol using OTEC hydrogen; and
5. Large-scale at-sea production of ammonia as a hydrogen carrier.

Achieving one or two of these visionary goals in a decade, if not sooner, will accelerate global implementation of the OTEC technology. To achieve some of these goals in the foreseeable future, an extraordinary global collaboration of leading industrial and investors will be required, potentially with a support from the United Nations (U.N.). C-footprint analysis is performed to demonstrate CO_2 abatement potentials by displacement of carbon-based power generation and production of commodity products. The technology status is presented and risk-management matrix (RMM) is evaluated for implementing the OTEC technology for achieving the five-step visionary goals.

2.1 OTEC Energy for the Island States

Small Island Developing States (SIDS) as well as other island states heavily rely on petroleum-liquid based power generation, specifically fuel oil and diesel. For example, power generating capacity of Mauritius and Reunion are 479 MW and 436 MW, respectively [2]. Fossil energy supplies 50% to 80% of power, with remainder from hydro and bagasse or biomass. The refined petroleum fuel is generally imported from an open market. The uncertainty of supply and price for refined petroleum fuel on a long-term basis has adverse impact on the economic sustainability of the island states as pointed out at the UN-sponsored SIDS conference in Mauritius [3]. As a result, the island states are actively pursuing renewable energy, specifically solar panels and wind turbines [4,5]. OTEC base-load power generation combined with intermittent power sources such as solar and wind turbines could make the island states free from petroleum-based power generation. The challenging task for the OTEC advocates and technology developers is to establish credible techno-economic and environment merits for an integrated power generation based on daily power demand profiles. With new generation of electric vehicles [6], the integrated power system will provide a ***back-bone system*** for sustainable petroleum-fuel free economic sustainability of the island states.

2.2 Green Ammonia

The global annual consumption of ammonia is 156 million metric tonnes (MMTA), with leading consumption in China, India and North America. Ammonia is exclusively produced with the Haber-Bosch process in which hydrogen and nitrogen are reacted at high pressure using catalytic reactors. The process requires a source of hydrogen and energy – thermal and electric – in the manufacturing process. Ammonia production in the U.S. is based on natural gas, while majority of ammonia production in Europe and Asia is based on heavy oil, petroleum coke and coal with high CO_2 emission. Ammonia is globally traded with sea-going tankers transporting ammonia over thousands of miles and via pipeline over the land.

Ammonia production from an energy-efficient natural-gas based plant consumes about 11,000 kWh/tonne of ammonia, with a C-footprint of 1.8 tonnes CO_2/tonne ammonia. However, the C-footprint of global ammonia production is more than 2.8 tonnes CO_2/tonne of ammonia due to the use of petroleum coke and coal. In the early part of the OTEC development, OTEC pioneer Dr. Avery proposed OTEC plantships for ammonia production [7]. The follow-up design study of OTEC plantships incorporated the recent technology developments, including aluminium heat exchangers, to evaluate techno-economic merits of at-sea production of ammonia, along with desalinated water [8]. The design study incorporated the emerging technology of solid-state ammonia synthesis which promises to be more than 30% energy efficient than natural-gas based Haber-Bosch process. With carbon-credit, "***green***" ammonia produced on large scale (> 500 tonnes/day) by OTEC plantships would be cost competitive in the present global market. Fig. 1 presents a concept design of satellite OTEC plantships for large-scale ammonia production with co-production of desalinated water.

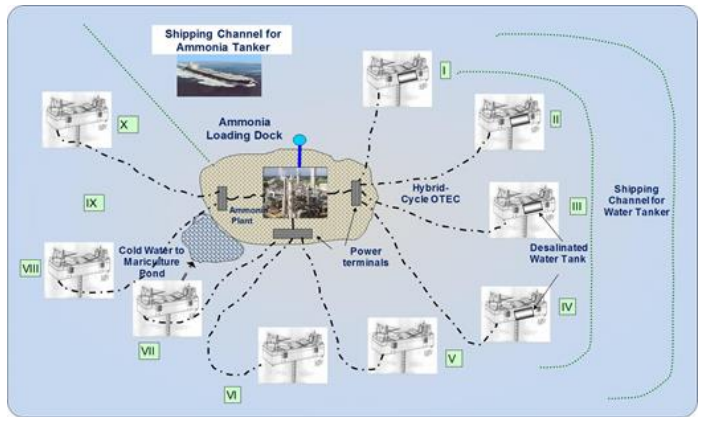

Figure 1: Satelite OTEC plantships for large scale ammonia production

2.3 Seawater Desalination

The global demand of fresh water is rapidly increasing due to the population growth, industry expansion in emerging markets, development of alternate energy sources, and adverse impacts of sea levels. An extensive study of ***Energy-Water Nexus*** is presented in a recent US DOE report [9]. The scope can be further expanded to ***Energy-Water-Food Nexus*** on a global scale. With impending climate variability and corresponding weather patterns specifically impacting the island and coastal states, the need for production of desalinated water is expected to rapidly increase in the foreseeable future. Among renewable energy sources, OTEC is a unique technology for co-production of power and desalinated water.

Different OTEC design options for production of desalinated water are:

a. Open cycle with surface condenser – demonstrated with 210 kW land-based pilot plant in Hawaii;
b. Ocean thermal desalination (OTD) – extension of commercial thermal desalination;
c. Hybrid OTEC cycle – coproduction of power and desalinated water [10,11], Fig. 2;
d. Reverse-Osmosis (RO) with OTEC power – use of deep-ocean cold water for desalination that minimizes the use of chemicals for controlling biofouling.

OTEC powered desalination has high potentials for near-term implementation for the island states, as they are experiencing scarcity of clean water for human consumption with direct impact on health.

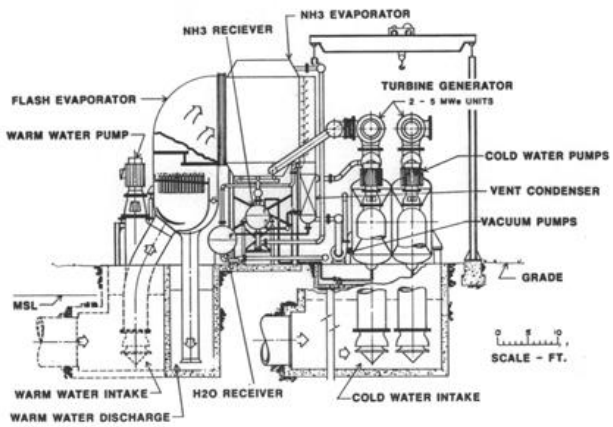

Figure 2: OTEC hybrid cycle for co-production of power and desalinated water

2.4 Conversion of CO_2 to Specialty Chemicals

CO_2 capture and sequestration (CCS) is being pursued, specifically for coal utility plants as demonstrated at the recent US DOE project review meeting [12]. However, high costs associated with CCS and corresponding impact on the cost of energy (COE) have prohibited global implementation of CCS. The recent emphasizes on utilization of captured CO_2 has inspired different technologies for conversion to value-added products to offset the CCS costs. Besides small-scale use of CO_2 (for example, in carbonated drinks), large-scale utilization of captured CO_2 to value-added products needs to be pursued. E3Tec is pursuing conversion of CO_2 to high-value alkyl carbonates that have application in manufacturing poly carbonate, in lithium-ion batteries and as environmentally benign solvents [13]. Other value-added products from CO_2 are: a) methanol b) cement; c) micro-algae based biochemicals; and d) graphene.

OTEC can play a key role in conversion of captured CO_2 to commodity chemical methanol as depicted by Fig. 3 for OTEC plantships in the Gulf of Mexico. Liquified CO_2 captured from coastal and interior utility and industrial plants can be transported to the OTEC plantships via tankers. Hydrogen is produced on board by electrolysis of desalinated water using OTEC power. Methanol is produced by catalytic reaction of hydrogen and CO_2. New catalysts are being developed for an energy efficient methanol production [14]. The annual global methanol production is 90 million metric tonnes with growth rate of about 9%. OTEC plantships for methanol production by utilization of captured CO_2 would fulfil the growth market with appealing economic and environmental benefits.

Figure 3: OTEC platships for CO_2-based methanol

3 CO2 ABATEMENT

3.1 Current Practices

The global annual demand for electricity is projected to be 25.6 million GWh in 2020 [15] that would generate about 15 billion tonnes of CO_2 annually. Table 1 presents the projected distribution of electric generation full with implementation of climate change policy and practice (CPP). It shows that in spite of expanded implementation of non-carbon electricity generation by nuclear and renewable energy, fossil fuel will continue to dominate. The projection is based on renewable energy consisting of hydro, solar panels and wind turbine; it does not include OTEC. To change the projected trend, an accelerated implementation of OTEC is required with the initial focus on the island markets. The projection presented in Table 1 does not consider expanded use of electric vehicles, which is supposed to dominate by 2040 [6]. Recently, four major countries have announced plan for implementation of electric vehicles by 2030. Such a plan will require significant new electric generation capacity. Balancing the liquid fuel vs. electricity in the foreseeable future is a challenging task that require a global initiative.

	2012	2020	2030	2040	Growth
Total World	**21.6**	**25.7**	**30.7**	**36.3**	**1.9%**
Petroleum	1.1	0.9	0.6	0.6	-2.2%
Natural Gas	4.8	5.5	7.5	10.0	2.6%
Coal	8.6	9.4	9.6	10.2	0.6%
Nuclear	2.3	3.1	3.9	4.5	2.3%
Renewable	4.7	6.9	9.1	11.1	3.1%

Table 1: Global annual electicity consumption, million GWh

3.2 OTEC Based Technology

Table 2 presents CO_2 abatement potentials with different market penetration levels by 2040. As expected, displacing coal and even natural-gas based power generation by 10%

would reduce annual CO_2 emission by 1.5 billion tonnes. With increasing use of electric vehicles, there would be need to expand electric power generation that can be implemented for the island states. This will result into additional CO_2 abatement by displacing liquid fuel for transportation with OTEC electric power. Additional abatements will be based on at-sea production of energy carriers, such as ammonia, and infrastructure for conversion to electricity. The next targets for implementation of OTEC are ammonia and desalinated water, where future demands can be provided by OTEC, without displacing the existing plants. The driving force for methanol production OTEC plantships is conversion of captured CO_2 to methanol at a competitive cost to commercial manufacturing.

	Global CO_2 Emission	**CO_2 Abatement**
Total	**16.85**	**2.03**
Electricty @ 10%	15.0	1.5
Ammonia production	0.84	0.42
Desalinated water	0.81	0.41
CO_2 based methanol	0.2	0.1

Table 2: Potential OTEC based CO_2 abatement in terms of billion tonnes per year

4 PATH FORWARD

As stated earlier, significant technical progress has been made and the major technical barriers have been removed. Despite these significant developments, not a single commercial OTEC plant was installed due to low energy costs and lack of industrial interests in the OTEC technology. There is a ***Window of Opportunity*** for global implementation of the OTEC technology for power generation as well as production of commodity products. Industrial organizations and entrepreneurs are actively pursuing for deployment of the first commercial OTEC plant; however, techno-economic barriers are hindering the implementation. The five-step visionary goal strategy provides the basis for developing a roadmap for commercialization of the OTEC technology.

A strategic path forward consists of the following steps:

1) Establishment of an international committee to develop a roadmap;
2) Development of a roadmap and presentation to international organization(s), such as U.N.; and
3) Public-private partnership for deploying the first generation of OTEC plants globally.

REFERENCES

[1] "Key Electricity Trend" *Excerpt from Electricity Information*, International Energy Agency, 2016.

[2] A. Garcia, "Renewable Energy Potentials of Small Island States," *Global Energy Network Isnstitute* (GENI), 2008.

[3] *UN Conference on Small Island Developing States*, Mauritius, 2005.

[4] "Renewable Energy Opportunities for Island Tourism," *International Renewable Energy Agency (IREA)*, Europe, 2014.

[5] S. Szabo, I. Kougias, M. Girona and K. Bodis, "Sustainable Energy Portfolio for Small Insland States," *Sustainability*, 2015.

[6] "Electric Vehicles on the Charge," *Morgan Stanley Research – Blue Paper*, August, 2017.

[7] W. Avery, "A Role of Ammonia in Hydrogen Economy," *Int. J of Hydrogen Energy*, vol. 13, 1988.

[8] C. Panchal, P. Pandolfini and W. Kumm "Ocean Thermal Plantships for Production of Ammonia as Hydrogen Carrier," *Argonne National Laboratory Report*, ANL/ESD/09-6, 2009.

[9] "The Water-Energy Nexus: Challenges and Opportunities," *US Department Energy Report*, June 2014.

[10] C. Panchal and K. Bell, "Simultaneous Production of Desalinated Water and Power Using Hybrid-Cycle OTEC Plants," *J of Solar Energy*, vol. 109, 1987.

[11] T. Rabas, C. Panchal and L. Genes, "Design and Cost of Near-Term OTEC Plants for Produciton of Desalinated Water and Power, " *Solar Energy in 1990's, ASME Publication*, 1990.

[12] 2017 NETL CO_2 Capture Technology Project Review Meeting, August 2017. (Online): http://www.netl.doe.gov/events/2017-tech-review.

[13] C. Panchal, J. Prindle, R. Sturtz and R. Doctor, "Utilization of CO_2 for Conversion to Alkyl Carbonates," *TechConnect SBIR/STTR Annual Conference*, Washington DC, 2017.

[14] M. Perez-Fortes, J. Schoneberger, A. Boulamanti and E. Tzimas, "Methanol Synthesis using Captured CO_2 as Rawmaterisl: Techno-Economic and Environment Assessment," *Applied Energy*, vol. 161, 2016.

[15] "International Energy Outlook 2017" *US Energy Information Agency*, 2017 (Online) http://www.eia.gov/outlooks/ieo/electricity.php.