Mechanical Engineering Research; Vol. 7 No. 1; 2017
ISSN 1927-0607 E-ISSN 1927-0615
Published by Canadian Center of Science and Education

# Deep-Subsea OTEC

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Received: June 24, 2016 Accepted: July 9, 2016 Online Published: May 30, 2017

doi:10.5539/mer.v7n1p1 URL: https://doi.org/10.5539/mer.v7n1p1

**Abstract**

A deep-subsea OTEC concept is simulated, and a threefold increase in exergy efficiency can be achieved as to the topside one. On the environmental aspect, a deep-subsea OTEC concept can bring about negative $CO_2$ emissions, which poses a positive environmental risk. On the economics, with appropriate public funding, a 100 MW deep-subsea OTEC asset would cost about $USD_{2010}$ 600 million. On the life-cost of energy, values between 40-60 $USD_{2010}$/MWh are predicted.

**Keywords**: ocean $CO_2$, ocean energy, OTEC, renewable energy, solar energy

## 1. Introduction

This paper proposes a concept design for a deep-subsea ocean thermal energy conversion asset (OTEC) as an alternative to topside. Such a concept joins the heat source (tropical surface ocean water) to the heat sink (deep ocean water) by an insulated pipe to bring the warm surface ocean water down to the deep-subsea facility. The key advantages are to eliminate $CO_2$ upwelling from the deep ocean waters, and to minimize investment and costs for no need of naval structures and human facilities.

The physical principle of the OTEC energy route is similar to the geothermal one. Both ones are characterized by utilizing Rankine-derived thermodynamic power cycles. In the tropics, heat sources stem from the surface ocean waters, and heat sinks from the deep waters below 800 m depth. Since the sun is the primary heat source, it is acceptable to qualify the OTEC energy route as a kind of solar power with inherent heat storage.

Investments on OTEC include large equipment needed to convert into electricity the low thermal energy density from the tropical oceans. Nonetheless, there are two positive expectations for economic consideration:

1) 90% operation capacity (Avery & Wu, 1994), for OTEC should not present the issues of intermittent energy supply from direct solar and wind power, or from rainfall regimes of the hydropower, or from crop seasonality of bio-fuels;

2) Besides electricity, other deliverables are possible as desalinated seawater and cold water for air conditioning or aquiculture systems.

Cornelia and Davis (2012) carried out a comparison study for the renewable ocean energy options, and the conclusion is the OTEC energy route is the best fit for a high energy and carbon prices scenario. These can provide competitive economic performance indicators in locations with no access to hydropower or high fuel costs. Ocean islands or tropical coastal regions may benefit from the OTEC deliverables (Fachina, 2016). In case of potential artificial islands or ocean cities in a future scenario, OTEC can be one of the components in a synergic renewable ocean energy portfolio, together with offshore wind power, solar power, and others such as currents, tides and waves. In terms of planetary technical energy resource, ocean thermal gradients account for about 7 TW (Rajagopalan & Nihous, 2013).

## 2. Concept Design of a Deep-Subsea OTEC Asset

Equation (1) is an exergy model (exergy per unit mass) (Callen, 1985), which stems from the complete Legendre transformation of energy (Note 1). The functions **h** (enthalpy) and **s** (entropy) stem from thermodynamic functions of working fluids. If there are chemical, nuclear reactions in the power cycle, energy potentials (**μ**), together with variation in mol, atomic numbers (**N**), shall be considered. The gravity force depends on gravity field (**g**) and mass.

In case of OTEC, the term with energy potential does not apply for there are no chemical, nuclear reactions in the power cycle, only heat transfers. The deep ocean water (DOW) is the heat sink, for which there must have reference values for the temperature, enthalpy and entropy. The surface ocean water (SOW) is the heat source. Also, any fluid column (**L**) above the water line becomes important, and undesirable, if the water pumps are not installed below the water line.

$$\varphi = \Delta h - T\Delta s - \mu \Delta N - g\Delta L \quad (1)$$

Figure (1) shows the thermodynamic power cycle utilized by the Author for the numeric simulation.

The Equation set (2) comprises coupled steady-state and energy balance equations, which build the working model for the simulation. The Author has utilized a software tool with built-in thermodynamic functions, the ammonia-water binary working fluid included. Equation (2a) calculates the power cycle overall exergy efficiency by solving for **η**. Equation (2b) establishes the overall energy balance in the power cycle, as well as Equation (2c) for electricity only. Equation (2d) establishes the energy balances for every system depicted in Figure 1.

On the working fluid, research and development activities since the 1980´s have leaded to the utilization of the ammonia-water mixture on the OTEC power cycles for its larger enthalpy gap between the liquid and the vapor phases than with ammonia only (Kalina, 1982).

$$W_{net} = \eta \varphi m_{SOW} \quad (2a)$$

$$Q_i^i + W_{gross} = 0 \quad (2b)$$

$$W_i^i = 0 \quad (2c)$$

$$(\eta Q)_i + (\eta W)_i = 0 \quad (2d)$$

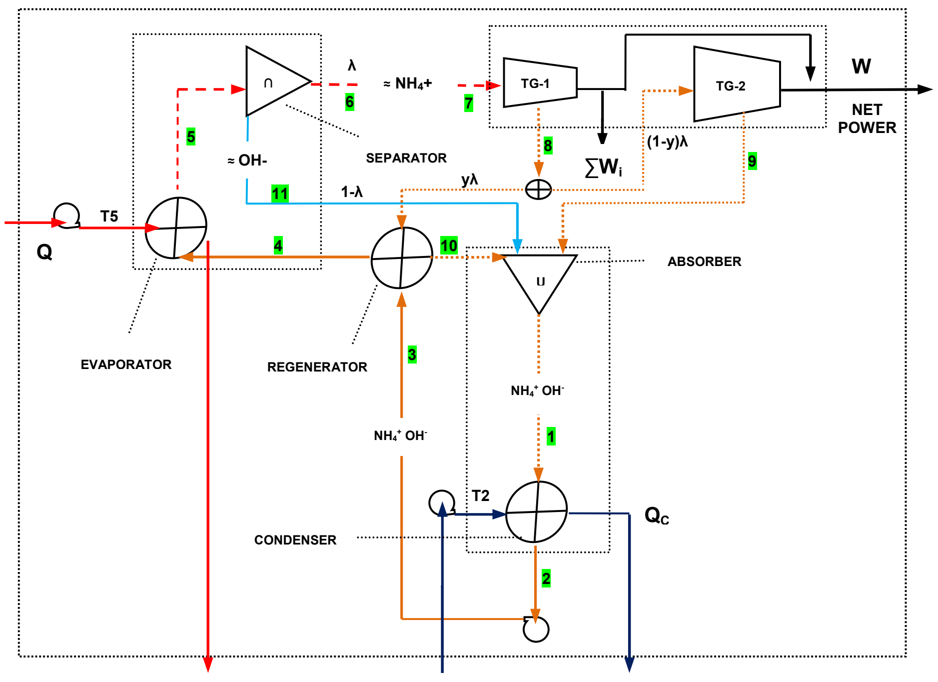


Figure 1: The Uehara®´s power cycle

Table 1 shows three numeric simulations: the Vega´s (Vega & Michaelis, 2010), the Ouchi´s (Ouchi, Jitsuhara, & Watanabe, 2011), and the Author´s. The missing data in Table 1 are not available.

The performance metrics consider electricity as the only output. The Ouchi´s paper does consider desalinated seawater as an output besides electricity; nevertheless, electricity has to be used for actually making desalinated seawater and pumping it to onshore or offloading it to a tanker ship. The more desalinated seawater to make and pump, the less deliverable electricity becomes available and vice-versa.

Table 1. Numeric simulations

| Design attribute | Vega´s | Ouchi´s | Author´s |
|---|---|---|---|
| Concept design | Topside | Topside | Deep-subsea |
| Power cycle type | $NH_3$-Rankine | Uehara® | Uehara® |
| Gross power | 80 MW | 5 MW | 5 MW |
| Net power | 53 MW | 3 MW | 3 MW |
| Ancillary electric consumption | Not available | Not available | 5% gross power |
| SOW temperature | 299 K | 298 K | 299 K |
| DOW temperature | 278 K | 278 K | 279 K |
| SOW flow | 264.6 $m^3$/s | 14.5 $m^3$/s | 4.7 $m^3$/s |
| Heat exchanger (HX) effectiveness | Not available | Not available | 75% |
| Turbo generator efficiency | Not available | Not available | 80% |
| Pumping efficiency | Not available | Not available | 75% |
| HX inlet-outlet temperature gap | 3 K | 3 K | 3 K |
| HX pressure loss | NA | NA | 1.5 bar |
| Seawater flow velocity | 2.0 m/s | 2.0 m/s | 2.0 m/s |
| Piping internal wall roughness | NA | NA | 50 μm |
| **Performance metrics** | | | |
| Overall exergy efficiency | 6% | 7% | 22% |
| Energy content (as to SOW) | 0.20 MJ/$m^3$ | 0.21 MJ/$m^3$ | 0.64 MJ/$m^3$ |

Note: Uehara® (Noda, Ikegami, & Uehara, 2002).

From the performance metric results, the deep-subsea OTEC concept presents values about three times larger as to the topside ones. The former´s top advantages are lower seawater flows per unit power, for there is no internal consumption of desalinated seawater, less ancillary electric consumption, and less-energy intensive seawater pumping due to the higher water density in the deep sea.

Depending on economic constraints, further improvements can be achieved by state-of-the-art heat exchangers, which would raise the inlet-outlet temperature gap, and by lowering the values of the seawater flow velocity and the piping internal wall roughness.

Equation (3) models the $CO_2$ relative concentration in air-to-water interfaces (R, the Revelle Factor) (Weiss, 1974). Such a concentration varies between 8 and 15, depending on the $CO_2$ temperature and concentration at the sea level atmosphere. As a base case, the Author assumes that to be 10.

$$R = \frac{\Delta[CO_2]_{ar} / [CO_2]_{ar}}{\Delta[CO_2]_{água} / [CO_2]_{água}} \quad (3)$$

The concentration gradient of dissolved $CO_2$ in the South Atlantic increases vertically from 2.0 mol $CO_2$/t-water at sea level up to 2.2 mol $CO_2$/t-water at 1,000 m-depth (Zeebe & Wolf-Gladrow, 2001). Nevertheless, local measurements ought to be made due to vertical and horizontal ocean current conditions.

For the onshore and the offshore topside assets (with long DOW pipe), there are $CO_2$ positive emissions to the atmosphere because DOW (with higher $CO_2$ concentration) is pumped upwards the sea level (with lower $CO_2$ concentration).

For the deep-subsea asset (with long SOW pipe), there are $CO_2$ negative emissions, or capture from the atmosphere, because SOW (with lower $CO_2$ concentration) is pumped downwards to the sea bottom (with higher $CO_2$ concentration).

From Equation (3) and the concentration gradient of dissolved $CO_2$ in the South Atlantic, there would be about 11,700 t $CO_2$/yr negative $CO_2$ emissions for a 5 MW gross deep-subsea OTEC asset, with 90% operational capacity.

Figure 2 illustrates a concept design of a deep-subsea OTEC asset. The SOW pipe has to be robustly insulated for a 1 K maximum temperature decrease (which is a symmetric design requirement for a DOW pipe in case of a topside facility). The SOW is pumped downwards the evaporator intake in the deep sea, and then upwards enough for safely discharging it away from the DOW intake (Fry, Adams, & Jirka, 1977). The DOW has to be pumped through the condenser, and then upwards enough for safely discharging it away from its intake (Fry, Adams, & Jirka, 1977).

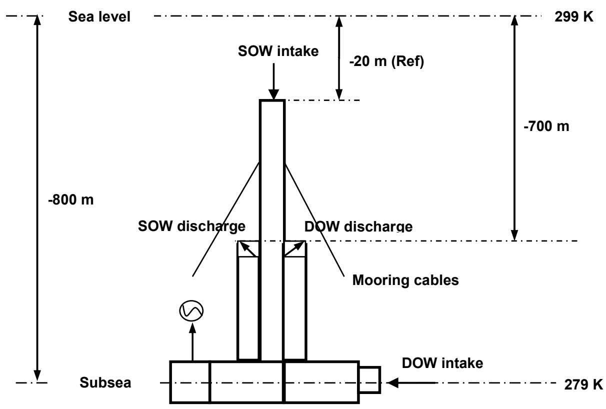


Figure 2. Concept design of a deep-subsea OTEC asset (not to scale)

## 3. Economics of a Deep-Subsea OTEC Asset

On the investment (**I**), Equation (4) stems from the Vega´s model (Vega, 2010) for estimating the investment on first-generation topside OTEC assets, with 2010-based USD values. Specifically for a deep-subsea OTEC asset, investments are expected to be about 30% less than for topside (Note 2) (Osmundsen, 2011). In the Equation (4), the 0-subscript means the currency values shall be converted to the same time base, usually the production start-up as time zero.

Table 2 compares normalized investments between the topside and the deep-subsea concepts. Technical services comprise business case and initial engineering studies, which are assumed to cost the same for both concepts. The other activity blocks differ substantially for the inherent deployment nature of the deep-subsea concept as to the topside one: no need for floating naval structures and related crew needs. Specifically for the deep-subsea equipment, their higher costs should be offset by even higher ones for the floating naval structures and human HSE systems in the topside concept.

Table 2. Normalized investments

| Activity block | Top | Deep | Differences Deep as to Top (base case) |
|---|---|---|---|
| Technical services | 5 | 5 | - |
| Onshore assemblies | 20 | 10 | No floating and human HSE systems |
| Offshore assemblies | 60 | 45 | Less workmanship and related HSE systems |
| Commissioning | 15 | 10 | No human HSE systems to commission |
| Grand totals | 100 | 70 | |

Figure 3 displays Equation (4), with $10\text{ MW} \leq \dot{\mathbf{W}} \leq 100\text{ MW}$ (red line). More accurate values should come up with the first commercial assets.

Equation (5) models the life-cost of energy (LCOE) as a function of the operational cost index $(\boldsymbol{\xi})$, and the net power ($\dot{\mathbf{W}}$). The assumptions for Equation (5) are: constant 10%/yr discount rate (**j**), 90% operation capacity (**α**) (1), and 25 years for the asset life time (**n**).

Figure 3 displays Equation (5), with $2\% \leq \xi \leq 10\%$, and $10\text{ MW} \leq \dot{W} \leq 100\text{ MW}$.

$$I_0 = k\dot{W}^{\lambda} \quad (4)$$

$$LCOE = \frac{I_0}{\dot{W}\Delta t}(1 + \xi_i x^{-i}) \quad (5)$$

$$\Delta t = 8{,}760\alpha n$$

$$x \equiv 1 + j$$

$$0 < \xi < 1$$

$$0 \leq i \leq n$$

On the operational cost index (**ξ**), it depends on the asset size and technology, and it is modeled as a fraction of the total investment at each time period. For simplification, it is set constant in all time periods. Such a factor shall get smaller if an effective carbon market actually comes true.

Public funding becomes fundamental due to higher risks involved before market maturity; nevertheless, the participation of private funding is necessary in order to promote better business efficiency under proper public regulation frameworks.

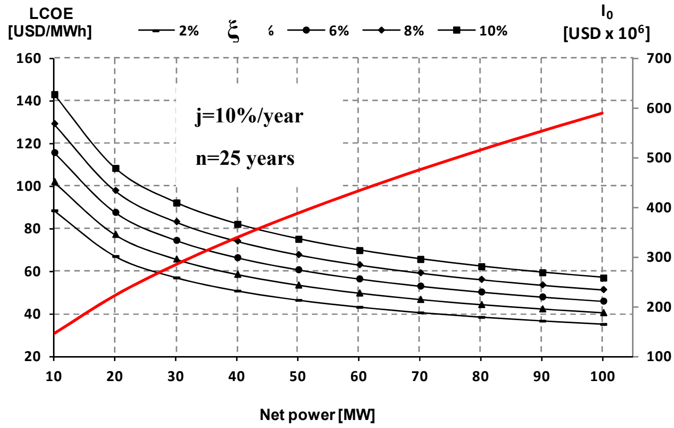


Figure 3. LCOE and 2010 investment estimates for first-generation deep-subsea OTEC

## 4. Conclusions

The OTEC energy route taps into the solar heat storage in the tropical oceans. An overall advantage of the OTEC route as to other renewable routes is the 90% expected operation capacity, which is far greater than direct solar or wind power. Out of the several OTEC configurations, the deep-subsea one offers advantages as to the topside ones.

On the technical aspect, a deep-subsea OTEC concept can have exergy efficiencies about threefold higher as to the topside ones.

On the environmental aspect, the deep-subsea OTEC concept can bring about negative $CO_2$ emissions, for it has to pump surface ocean water downwards the deep sea, which poses a positive environmental risk.

On the economical aspect, the deep-subsea OTEC concept can cost about 30% less than a topside one. An economic model for a 100 MW asset yields $USD_{2010}$ 600 million investments, and 40-60 $USD_{2010}$/MWh LCOE.

**Acknowledgement**

The Author thanks Petrobras for their receptivity to the OTEC energy route.

**Glossary**

**DOW**: Deep Ocean Water;
**g**: gravity field;
**h**: specific enthalpy;
**HSE**: Health, Safety and Environment;
**HX**: heat exchanger;
**I**: investment amount;
**L**: fluid column;
**LCOE**: Levelized Cost Of Energy;
**m**: either DOW, SOW or working fluid mass;
**N**: either mol or atomic number;
**OTEC**: Ocean Thermal Energy Conversion;
**P**: absolute pressure;
**Q**: either gross, net or internal heat;
**s**: specific entropy;
**SOW**: Surface Ocean Water;
**T**: absolute temperature;
**W**: either gross, net or internal work;
**α**: operational factor;
**η**: either energy or exergy efficiency;
**μ**: either chemical or nuclear potential;
**φ**: specific exergy (exergy per unit mass).

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**Notes**

Note 1. A Legendre transformation substitutes function´s first derivatives for the function itself. The complete Legendre transformation of energy is $\varphi = u(x) - x_i \partial_x u^i$, where **φ** is exergy, **u** is energy, and **x** represents energy independent variables. The Einstein´s summation convention over **i** is applied for the **u** partial derivatives to **x**. Such a convention is applied in all models for replacing the Σ symbol.

Note 2. The k-factor value in the Equation (4) is 53 x $10^6$ [USD/MW], which should be multiplied by 0.7 in order to account for the lower expected investment for the deep-subsea OTEC asset. The value of λ is 0.6.