ME301 Course Project

Thermodynamic Efficiency and Feasibility of Ocean Thermal Energy Conversion (OTEC) Systems"

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November 10, 2024

1 Abstract

This study investigates the viability of an Ocean Thermal Energy Conversion (OTEC) system for sustainable energy production, leveraging the temperature difference between warm surface seawater and colder deep-seawater. A 10 MW OTEC plant prototype, situated in Malaysia, is analyzed with a focus on its capacity to convert thermal energy into electricity using the Rankine cycle. Ammonia is employed as the working fluid due to its favorable thermodynamic properties.

Ocean Thermal Energy Conversion (OTEC) presents a promising renewable energy solution, particularly suitable for tropical regions with consistent surface water temperatures. This study examines a 10 MW OTEC plant design in Malaysia, aiming to evaluate the viability and efficiency of such systems. Ammonia was selected as the working fluid because of its efficient thermal properties, which enhance the Rankine cycle's effectiveness in this context.

The OTEC system operates on a closed Rankine cycle, incorporating an evaporator, turbine, condenser, and pump. Warm surface seawater heats the ammonia in the evaporator, causing it to vaporize. This vapor drives the turbine, generating electricity, and subsequently passes into the condenser, where it is cooled by cold deep-seawater. This process condenses the ammonia back to liquid form, allowing it to recirculate.

2 Introduction

2.1 Background and Need for Alternative Energy Systems

Currently, most of the world's energy is generated from fossil fuels, including coal, oil, and natural gas. While effective for meeting high energy demands, these sources produce significant greenhouse gas emissions, driving climate change and environmental degradation. With fossil fuel reserves depleting and their environmental impact becoming increasingly unsustainable, alternative energy solutions are urgently needed. Renewable technologies like solar, wind, and geothermal energy offer promising alternatives but come with limitations—such as weather dependence or specific geographic requirements—that hinder consistent energy supply.

2.2 Objective and Scope of the Project

This project explores the potential of Ocean Thermal Energy Conversion (OTEC) as a sustainable, alternative energy source. Focusing on a 10 MW OTEC plant in tropical ocean conditions similar to Malaysia's, we assess the thermodynamic, technical, and economic viability of this system. Using simulations and mathematical modeling, this study evaluates the power output, efficiency, and overall feasibility of OTEC, aiming to highlight its potential as a reliable substitute for conventional energy sources.

2.3 Overview and Advantages of OTEC

OTEC systems generate electricity by harnessing the temperature difference between warm surface seawater and cold deep-seawater, operating on a closed Rankine cycle with ammonia as the working fluid. The warm seawater heats and vaporizes the

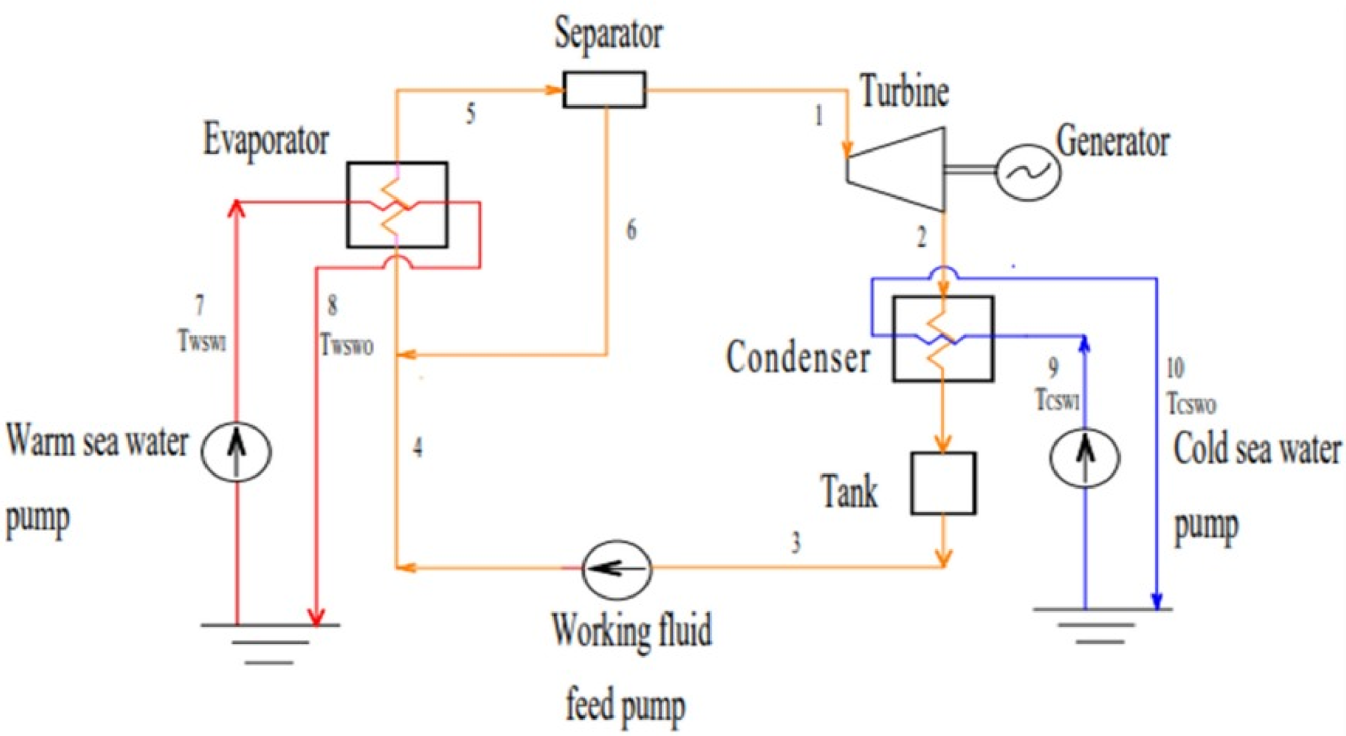

Figure 2.1: cycle showing the warm seawater, cold seawater, and NH_3 paths, with labels for the four main components (evaporator, turbine, condenser, and pump).

ammonia, which drives a turbine to produce electricity before being condensed by the cold seawater and recirculated. Ideal for tropical regions with a stable temperature difference of at least 20°C, OTEC can supply continuous, low-emission energy. Compared to other renewable sources, this system provides a stable base-load power supply and has a smaller land footprint, offering a viable solution for regions with limited land resources.

2.4 Previous Research and Comparison with Existing Technologies

OTEC research, ongoing for decades, initially focused on small-scale plants. Recent studies have assessed larger plants' economic feasibility, indicating competitive Levelized Cost of Electricity (LCOE) for tropical regions with high energy costs. Research efforts in Japan, Indonesia, and similar areas have centered on improving heat transfer in the evaporator and condenser, as well as minimizing energy losses during seawater pumping, particularly with ammonia as the working fluid. In contrast to solar and wind, OTEC's ability to generate steady energy independent of seasonal changes likens it to geothermal or hydroelectric power. While its efficiency (around 3–5%) is lower than fossil fuel plants, OTEC's zero-emission output and potential for desalination support make it a promising alternative for stable energy generation in tropical regions, despite higher initial costs.

3 Principles of OTEC from a Thermodynamics Perspective

3.1 Overview with diagram

The process involves the following steps

- **Heat Absorption :** Warm seawater from the surface heats the working fluid, causing it to evaporate in the evaporator.
- **Energy Conversion:** The ammonia vapor drives a turbine, generating power.
- **Condensation:** Cold deep-seawater condenses the working fluid back into a liquid in the condenser.
- **Cycle Continuation:** The working fluid is recirculated by a pump back to the evaporator, completing the thermodynamic cycle.

  We are considering Rankine cycle for calculation and analysis, the detail diagram is shown below

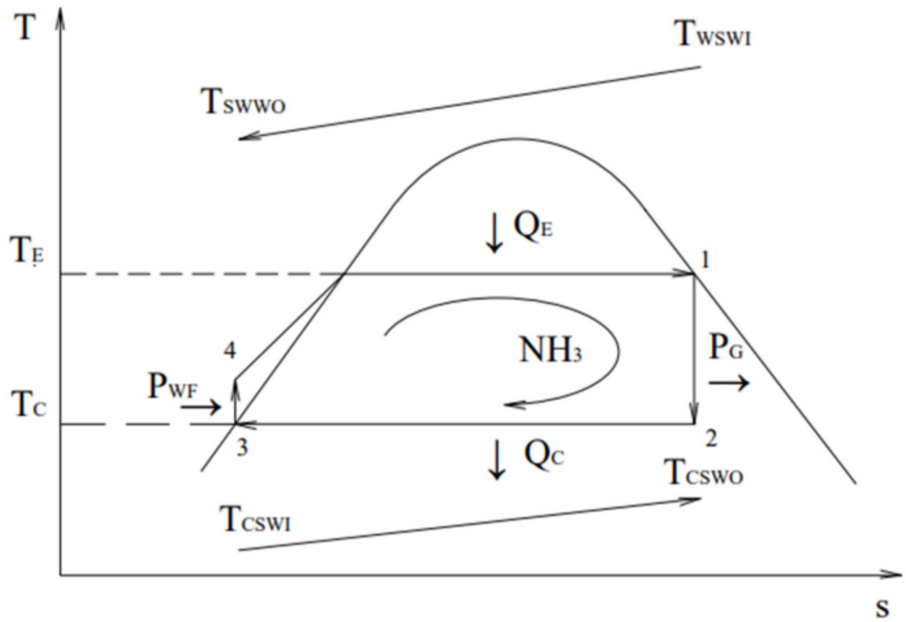

Figure 3.1: T-s diagram illustrating the thermodynamic states and transitions (1 to 2, 2 to 3, 3 to 4, and 4 to 1)

4 Thermodynamic Calculations for Each Process

4.1 Process 4 → 1 (Evaporation)

In this process, NH_3 absorbs heat (Q_E) from the warm seawater and vaporizes in the evaporator.

Heat Absorbed in Evaporator (Q_E):

$$Q_E = m_{\mathrm{NH_3}} \cdot (h_1 - h_4)$$

where:

- $m_{\mathrm{NH_3}}$ is the mass flow rate of NH_3.
- h_4 and h_1 are the enthalpies of NH_3 at states 4 and 1, the inlet and outlet of the evaporator respectively.

Evaporator Heat Transfer Area (A_E):

$$A_E = \frac{Q_E}{U_E \cdot \Delta T_{\mathrm{m,E}}}$$

where:

- U_E is the overall heat transfer coefficient for the evaporator.
- $\Delta T_{\mathrm{m,E}}$ is the logarithmic mean temperature difference between NH_3 and warm seawater in the evaporator.

4.2 Process 1 → 2(Expansion)

In this process, the high-pressure NH_3 vapor expands in the turbine, doing work (W_{turbine}).

Work Done on Turbine (W_t):

$$W_{\mathrm{turbine}} = m_{\mathrm{NH_3}} \cdot (h_1 - h_2)$$

where h_1 and h_2 are the enthalpies at the inlet and outlet of the turbine, respectively.

Turbine Efficiency (η_T):

$$\eta_T = \frac{W_{\mathrm{turbine}}}{W_{\mathrm{ideal}}}$$

where W_{ideal} is the theoretical work without any losses. Therefore, the work supplied to the generator:

$$W_{\mathrm{turbine}} = \eta_T \cdot W_{\mathrm{ideal}}$$

4.3 Process 2 → 3 (Condensation)

In this process, the NH_3 vapor condenses by releasing heat (Q_C) to the cold seawater in the condenser.

Heat Released in Condenser (Q_C):

$$Q_C = m_{NH_3} \cdot (h_2 - h_3)$$

where h_2 and h_3 are the enthalpies of NH_3 before and after condensation.

Condenser Heat Transfer Area (A_C):

$$A_C = \frac{Q_C}{U_C \cdot \Delta T_{m,C}}$$

where:

- U_C is the overall heat transfer coefficient for the condenser.
- $\Delta T_{m,C}$ is the logarithmic mean temperature difference between NH_3 and cold seawater in the condenser.

4.4 Process 3 → 4 (Compression)

In this process, the liquid NH_3 is pumped back to a higher pressure before entering the evaporator.

Pump Work (W_p):

$$W_{pump} = m_{NH_3} \cdot (h_4 - h_3)$$

where h_3 and h_4 are the enthalpies of NH_3 before and after pumping respectively.

Pump Efficiency (η_P):

$$\eta_P = \frac{W_{pump,ideal}}{W_{pump}}$$

where $W_{pump,ideal}$ is the theoretical pump work assuming no losses.

4.5 Net Power Output (P_N) and Thermal Efficiency

The net power P_N is defined as in Equation (4.1):

$$P_N = P_G - (P_{WSW} + P_{CSW} + P_{WF}) \tag{4.1}$$

where:

- P_G is the generated power (gross power).
- P_{WSW} is the warm seawater pumping power.
- P_{CSW} is the cold seawater pumping power.
- P_{WF} is the working fluid pumping power.

These are further defined by the following equations:

$$P_G = m_{WF} \cdot \eta_T \cdot \eta_G \cdot (h_1 - h_2) \tag{4.2}$$

$$P_{WSW} = \frac{m_{WSW} \cdot \Delta P_{WSW}}{\eta_{WSW} \cdot \rho_{WSW}} \tag{4.3}$$

$$P_{CSW} = \frac{m_{CSW} \cdot \Delta P_{CSW}}{\eta_{CSW} \cdot \rho_{CSW}} \tag{4.4}$$

$$P_{WF} = \frac{m_{WF} \cdot \Delta P_{WF}}{\eta_{WF} \cdot \rho_{WF}} \tag{4.5}$$

where:

- ΔP_{WSW} is the total pressure difference for the warm seawater.
- ΔP_{CSW} is the total pressure difference for the cold seawater.
- ΔP_{WF} is the total pressure difference for the working fluid.
- m_{WF} is the mass flow rate of the working fluid.

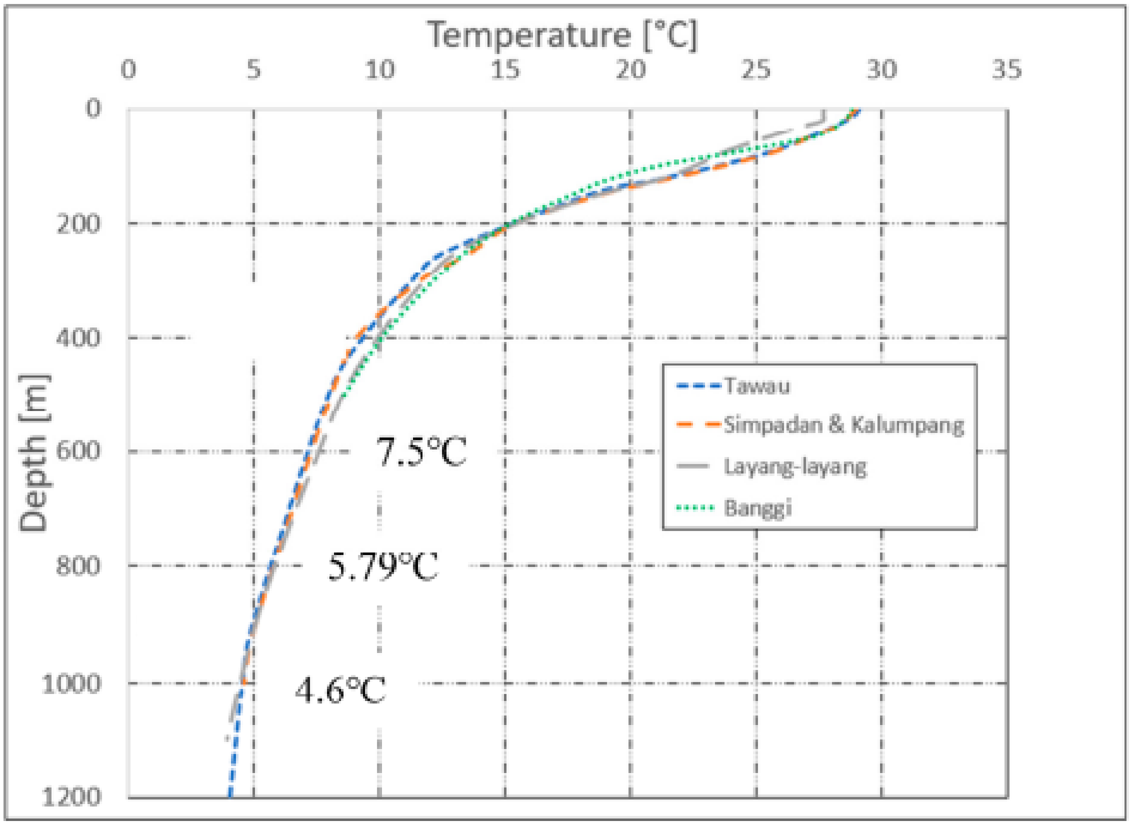

Figure 2. Depth and deep seawater temperature profile of several potential sites in Sabah at 1000 m, 800 m, and 600 m, respectively. For simulation purpose, the applied data for Kalumpang was retrieved from Japan Oceanographic Data Center (JODC) (2020) 1000 m (4.6 °C), 800 m (5.79 °C), and 600 m (7.5 °C), respectively.

- m_{WSW} is the mass flow rate of the warm seawater.
- m_{CSW} is the mass flow rate of the cold seawater.
- η_T is the turbine efficiency.
- η_G is the generator efficiency.
- η_{WSW}, η_{CSW}, and η_{WF} are the efficiencies of the warm seawater pump, cold seawater pump, and working fluid pump, respectively.
- ρ_{WSW}, ρ_{CSW}, and ρ_{WF} are the densities of warm seawater, cold seawater, and the working fluid, respectively.

Thermal Efficiency (η_{thermal}): The efficiency of the Rankine cycle is calculated as the ratio of the net power output to the heat absorbed in the evaporator:

$$\eta_{\text{thermal}} = \frac{P_N}{Q_E}$$

4.6 Key Parameters for Optimization

For cost-effectiveness, OTEC systems are designed to minimize the total heat transfer area $A_T = A_E + A_C$ by maximizing the temperature differential between the warm and cold seawater.

The objective function γ, representing cost per unit power output, is minimized to achieve economic viability:

$$\gamma = \frac{A_T}{P_N}$$

Optimizing the system involves balancing parameters such as the heat exchanger area, turbine efficiency, and pump efficiency to achieve the minimum γ while maximizing η_{thermal}.

5 Cost analysis for OTEC Systems

Ocean Thermal Energy Conversion (OTEC) systems are not yet widely deployed, so cost estimates remain uncertain. Initial investment costs vary significantly depending on the plant size and cycle type. Closed-cycle (CC) OTEC plants with capacities ranging from 1 MW to 50 MW have initial costs between $0.0224 and $0.00656 per kW, while open-cycle (OC) plants show a broader range, from $0.0259 per kW for a 1 MW OC plant to $0.01102 per kW for a 50 MW plant. Larger, more complex OTEC systems require a higher capital investment.

Electricity costs for OTEC vary depending on the plant scale. A 2010 study by the University of Hawaii estimated OTEC electricity costs at 94 cents per kWh for a 1.4 MW plant, 44 cents per kWh for a 10 MW plant, and 18 cents per kWh for a 100 MW plant. In 2015, Ocean Energy Systems under the International Energy Agency provided an estimate of approximately 20 cents per kWh for a 100 MW plant, and other studies project costs as low as 7 cents per kWh for larger OTEC plants. In comparison, other renewable sources such as utility-scale solar PV and wind power have lower costs, with 2019 estimates by Lazard placing them at 3.2–4.2 cents per kWh for solar PV and 2.8–5.4 cents per kWh for wind power.

According to a 2014 report by IRENA, small-scale OTEC plants could be economically viable if they also produce valuable by-products like fresh water or cooling, which are beneficial for communities of 5,000 to 50,000 residents. Scaling OTEC for larger installations, however, would lead to significantly higher installation and operational costs.

Type	**Closed Cycle (CC)**			**1st Open Cycle (OC)**			**2nd Open Cycle**	
Power (MW)	1 MW	10 MW	50 MW	1 MW	10 MW	50 MW	10 MW	50 MW
Heat Exchanger	3.2	28	100	3.5	35	128.6	5.8	179.9
Seawater System (Pipes and Pumps)	12	48	96	12.3	60	220.4	20.4	308.4
Turbine	2.4	20	48	3.7	25	55.1	6.1	128.5
Structure	3.2	12	60	4.4	15	55.1	7.3	77.1
Other	1.6	12	24	2	15	55.1	3	55.1
Total Cost (Million $)	22.4	120	328	25.9	150	551	42.9	771
Initial Cost (Million $ / kW)	0.0224	0.012	0.00656	0.0259	0.015	0.01102	0.0429	0.01542

Table 5.1: Initial Investment Costs of OTEC Systems

6 Simulation

6.1 Code of Cycle Efficiency Calculation

The following Python code calculates the efficiency of the Rankine cycle for an Ocean Thermal Energy Conversion (OTEC) system. It takes the evaporator and condenser temperatures (in Celsius) as inputs and returns the efficiency of the cycle based on chosen fluid.

```python
def calculate_rankine_efficiency(T_evap, T_cond, fluid):
    """
    Function to calculate the efficiency of a Rankine cycle given
    the evaporator and condenser temperatures in Celsius.

    Args:
        T_evap (float): Evaporator temperature in Celsius.
        T_cond (float): Condenser temperature in Celsius.

    Returns:
        float: The efficiency of the Rankine cycle.
    """
    # Convert temperatures to Kelvin
    T_evap_K = T_evap + 273.15
    T_cond_K = T_cond + 273.15

    # Get states for Rankine cycle
    # 3 -> 4 (Pump, isentropic)
    P3 = CP.PropsSI('P', 'T', T_cond_K, 'Q', 0, fluid)  # Condenser pressure (saturated liquid)
    h3 = CP.PropsSI('H', 'T', T_cond_K, 'Q', 0, fluid)  # Enthalpy at state 3
    s3 = CP.PropsSI('S', 'T', T_cond_K, 'Q', 0, fluid)  # Entropy at state 3

    P1 = CP.PropsSI('P', 'T', T_evap_K, 'Q', 1, fluid)  # Evaporator pressure (saturated vapor)
    P4 = P1  # Because Isobaric heating process in evaporator
```

```python

    h4 = CP.PropsSI('H', 'P', P4, 'S', s3, fluid)  # Enthalpy at state 4, at pump outlet

    # 4 -> 1 (Boiler, heat addition at constant pressure)
    h1 = CP.PropsSI('H', 'T', T_evap_K, 'Q', 1, fluid)  # Saturated vapor enthalpy at evaporator
    s1 = CP.PropsSI('S', 'T', T_evap_K, 'Q', 1, fluid)

    # 1 -> 2 (Turbine, isentropic)
    P2 = P3  # Because isobaric condensation process in condenser
    s2 = s1  # Because isentropic process in turbine
    h2 = CP.PropsSI('H', 'P', P2, 'S', s1, fluid)  # Approx. enthalpy at state 2 (isentropic)

    # Calculate heat added and work done
    heat_added = h1 - h4  # Boiler
    work_pump = h4 - h3   # Pump
    work_turbine = h1 - h2  # Turbine
    net_work = work_turbine - work_pump

    # Calculate efficiency
    efficiency = net_work / heat_added
    return efficiency
```

```python
T_evap = 27 # Evaporating temperature in degree Celsius
T_cond = 8 # Condensing temperature in degree Celsius
fluid = "Ammonia"
```

6.2 GitHub Repository and Comparison Table for Simulation

For the full simulation and additional resources, you can visit the GitHub repository:

Fluid	Efficiency
R12	5.97%
R22	5.99%
R32	5.99%
R123	6.02%
R1234yf	5.87%
R1234ze(E)	5.92%
R125	5.77%
R134a	5.93%
R141b	6.06%
R143a	5.85%
R152a	6.00%
R290	5.94%
R404A	5.71%
R407C	4.17%
R410A	5.87%
R507A	5.82%
Isobutane	5.96%
n-Butane	5.98%
Propylene	5.95%

Table 6.1: Comparison between different fluids based on above simulation

7 Comparison of OTEC with Wind and Solar Power

To further demonstrate the viability of Ocean Thermal Energy Conversion (OTEC) compared to wind and solar power, let's break it down based on several key factors such as energy output, land use, efficiency, and environmental impact. We'll also emphasize the advantage of utilizing the vast ocean areas available for OTEC, which allows for large-scale energy production.

7.1 Energy Generation Potential (Land and Area Use)

7.1.1 OTEC

Land Use: OTEC plants are typically located offshore, meaning that they do not require significant land area. The system relies on the temperature difference between surface and deep ocean water.
Energy Density: The energy density of OTEC depends on the local temperature gradient, typically ranging from 100 to 200 kW/km² of ocean surface area.
For example, in tropical regions like Hawaii or the Caribbean, an OTEC plant could generate significant power with minimal space, leveraging vast oceanic areas.
Example Calculation: If an OTEC plant utilizes 100 km² of ocean area, it could potentially generate:

$$100\,\mathrm{km}^2 \times 150\,\mathrm{kW/km}^2 = 15,000\,\mathrm{kW} = 15\,\mathrm{MW}$$

Given that large regions of the ocean are available, OTEC could be scaled up significantly.

7.1.2 Wind Energy

Land Use: Wind farms require large tracts of land, typically between 10 to 20 km² per MW, depending on the wind conditions and turbine size. Offshore wind farms, though they utilize sea areas, still require significant space between turbines for efficiency.
Energy Density: Offshore wind farms typically generate 4 to 8 MW/km², but this can vary significantly depending on wind speed and technology used.
Example: A large-scale offshore wind farm with an area of 100 km² might produce:

$$100\,\mathrm{km}^2 \times 6\,\mathrm{MW/km}^2 = 600\,\mathrm{MW}$$

Wind farms can generate much more power per unit area compared to OTEC, but they require considerable space and may face visual or environmental impacts.

7.1.3 Solar Energy

Land Use: Solar farms require large land areas as well, typically 5 to 10 acres per MW of installed capacity.
Energy Density: Solar energy generation is highly dependent on geographic location. In areas with good solar exposure, you might see 200-300 W/m² of solar irradiation, which translates to roughly 200 to 400 MW per square kilometer.
Example: A 100 km² solar farm could generate:

$$100\,\mathrm{km}^2 \times 250\,\mathrm{MW/km}^2 = 25,000\,\mathrm{MW} = 25\,\mathrm{GW}$$

Solar farms can provide significant power output, especially in sunny regions, but they need substantial land area and cannot operate at night.

7.2 Efficiency and Capacity Factor

7.2.1 OTEC

Efficiency: OTEC systems typically have low thermal efficiency (10-6% for Rankine cycles) due to the small temperature difference between the warm and cold water. However, this can be offset by constant, renewable energy production, 24/7.
Capacity Factor: OTEC can operate continuously (24/7), meaning a high capacity factor close to 100%, unlike wind and solar, which are intermittent.

7.2.2 Wind Energy

Efficiency: Wind turbines typically have an efficiency of 35-50%, depending on wind conditions, turbine design, and local geography.
Capacity Factor: Offshore wind farms typically have a capacity factor of about 40-50%, depending on the wind resource.

7.2.3 Solar Energy

Efficiency: Solar panel efficiency is typically 15-20%, but this varies based on technology.
Capacity Factor: Solar farms typically have a capacity factor of around 20-25%, as they only generate power during sunlight hours and are affected by weather conditions.

7.3 Environmental Impact and Sustainability

7.3.1 OTEC

Carbon Emissions: OTEC is essentially a zero-emission energy technology. Since it doesn't burn fossil fuels, it generates no CO_2 or particulate emissions.
Marine Impact: OTEC plants can have minimal environmental impact as they use deep ocean water and don't disrupt ecosystems significantly. They are self-contained offshore systems.
Sustainability: OTEC systems can provide baseload power, which is an important characteristic for sustainable energy production. The temperature gradient in the ocean is renewable and inexhaustible as long as there is sunlight to heat the surface.

7.3.2 Wind Energy

Carbon Emissions: Wind energy is also a clean source of power, with no CO_2 emissions during operation. However, manufacturing and installation of turbines do have a carbon footprint.
Land and Wildlife Impact: Wind turbines, especially on land, can pose threats to wildlife, such as birds and bats, and may lead to habitat disruption in some regions.
Sustainability: Wind is renewable and has a relatively low environmental footprint compared to fossil fuels.

7.3.3 Solar Energy

Carbon Emissions: Solar energy is carbon-free during operation. However, the production of solar panels involves energy-intensive processes and some emissions.
Land Use and Wildlife: Large-scale solar farms can impact local ecosystems, though their footprint is generally less disruptive compared to fossil fuel plants.
Sustainability: Solar energy is sustainable as long as the sun shines, but it depends on land availability and location.

7.4 Economic Viability

7.4.1 OTEC

Capital Costs: OTEC systems have high upfront costs due to infrastructure and deep-water technology, but they benefit from low operating costs. The cost of power can range from $0.10 to $0.15/kWh.
Operational Costs: Low operational costs, as there is no need for fuel, and minimal maintenance.

7.4.2 Wind Energy

Capital Costs: Offshore wind farms have high initial costs, generally around $2,000 to $6,000 per installed kW.
Operational Costs: Operating costs are lower, with significant savings on fuel costs, and maintenance is required for turbines.

7.4.3 Solar Energy

Capital Costs: Solar farms have moderate capital costs, around $1,000 to $3,000 per installed kW, but they require significant land and may have installation challenges.
Operational Costs: Solar has very low operating costs, but performance is highly dependent on location and sunshine.

7.5 Long-Term Viability

7.5.1 OTEC

The ocean covers more than 70% of the Earth's surface, providing vast untapped areas for OTEC systems. As long as there is a temperature difference between warm and cold ocean waters, OTEC can provide a constant, renewable power source. Unlike wind and solar, OTEC is not intermittent and can generate power 24/7.

7.5.2 Wind

Wind resources are only available in certain regions, and wind farms can face land-use and environmental challenges. Offshore wind, however, can make use of the vast ocean areas.

7.5.3 Solar

Solar energy is abundant but land-intensive, and its variability can limit its ability to provide consistent power. Solar systems' dependence on sunlight makes it more intermittent compared to OTEC.

7.6 Conclusion: Why OTEC?

7.6.1 Area Utilization

OTEC can tap into the vast ocean areas (which are significantly more abundant than land areas) to generate large-scale renewable energy, without competing for land space or resources. This makes OTEC a highly scalable technology, especially in tropical coastal areas.

7.6.2 Sustainability

OTEC is more sustainable in the long term compared to both wind and solar, as it provides constant, predictable energy, and is not affected by weather or time of day.

7.6.3 Complementary with Wind and Solar

OTEC could complement wind and solar energy in regions with high ocean temperature gradients, providing a base-load power supply when wind and solar generation fluctuate.

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