WHITE PAPER OTEC

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LIST OF ACRONYMS

AC	Alternating Current
CAPEX	Capital Expenditure
CC	Capital Costs
DC	Direct Current
FPSO	Floating, Production, Storage, and Off-loading
HDPE	High-Density Polyethylene
HXC	Heat Exchange Company
IRR	Internal Rate of Return
LCOE	Levelised Cost of Electricity
OMR&R	Levelised Operation, Maintenance, Repair and Replacement
OTEC	Ocean Thermal Energy Conversion
SIDS	Small Island Developing States

CONTENT

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that harnesses the temperature difference between warm surface waters and cold deep ocean waters to produce electricity.

1

INTRODUCTION

OVERVIEW OF OTEC

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that harnesses the temperature difference between warm surface waters and cold deep ocean waters to produce electricity. This innovative method of power generation holds great promise as a clean and renewable energy source, offering a range of applications that can address the world's growing energy needs while mitigating the impact of climate change. The concept of OTEC was first proposed in the early 1880s by the French engineer Jacques-Arsène d'Arsonval [1]. His student, Georges Claude, built the first OTEC plant in Matanzas, Cuba in 1930, which generated 22 kW of electricity with a low-pressure turbine [1].

There are two main types of OTEC systems: open-cycle and closed-cycle. Open-cycle OTEC uses seawater as the working fluid. In this system, warm surface seawater is introduced in a low-pressure compartment, causing it to boil and produce steam. Since the boiling point of water decreases as the pressure decreases, this process can occur at significantly lower temperatures than the standard boiling point of water at 100 °C under atmospheric pressure. The resulting steam is then used to drive a generator and is condensed by the cold seawater pumped up from below. Unlike the open-cycle OTEC, the closed-cycle system uses a working fluid with a low boiling point, such as ammonia or a refrigerant. In this system, warm surface seawater heats the working fluid, causing it to vaporise. The vaporised working fluid expands and drives a turbine, which is connected to a generator to produce electricity. After passing through the turbine, the vaporised working fluid is condensed by the cold seawater, and then pumped back to the evaporator to complete the cycle. Additionally, a hybrid-cycle system may also be considered, which combines features of both the open and closed cycles to enhance efficiency and productivity. In this system, electricity is first generated in a closed-cycle using warm seawater to vaporise the working fluid, which then drives a turbine to produce electricity. Then, instead of being immediately condensed, the vapour from the closed-cycle can be used to heat and vaporise additional seawater in an open-cycle process. This second stage increases the volume of steam available to drive the turbine or a second turbine, further increasing electricity production.

BENEFITS, CHALLENGES, AND EMERGING APPLICATIONS

The advantages of OTEC include its renewable nature, minimal environmental impact, and the ability to provide grid stabilising base-load power, unlike other intermittent renewable sources. However, the technology faces the typical challenges as other marine renewable energy systems, such as high initial costs and engineering solutions associated with operating in an offshore environment. Additionally, OTEC is most viable in regions where there is a significant temperature difference between surface and deep-waters, limiting its applicability to tropical and subtropical regions [2]. As pointed out by Fujita et al. [3], the temperature difference should be higher than 20°C in order to achieve net electrical power generation, good plant efficiency and economical outputs. Small temperature differences limit the thermal efficiency, which is a major hurdle in making OTEC competitive with other energy sources. This can be mitigated by locating OTEC projects at sites where a temperature difference of 25°C can be used.

Despite these challenges, OTEC has the potential to play a significant role in the global energy mix, particularly in island nations and coastal regions where energy options are limited, and the thermal gradient in nearby waters is favourable. Currently, OTEC is still considered an emerging technology, but it has the potential to produce terawatts of electrical power, globally. Some of the proven applications include:

Electricity generation

The primary application of OTEC technology is electricity generation. Warm surface water is used to vaporise a working fluid with a low boiling point, which drives a turbine connected to a generator. Cold water from the deep sea is then used to condense the vapour, completing the cycle. OTEC systems can produce a continuous and reliable source of clean electricity, making them suitable for powering remote islands and coastal regions [4].

Fresh water production

OTEC systems using sea-water as the working fluid can use the condensed water to produce desalinated water. This application is particularly valuable in arid regions and islands where fresh water is scarce [5, 6].

Aquaculture

OTEC systems can provide temperature-controlled water for aquaculture applications. By pumping clean, cold and nutrient-rich water from the deep sea to the surface, OTEC creates favourable conditions for fish farming, enhancing growth rates and reducing stress on aquatic species [5, 6].

Mariculture and Agriculture

Similar to aquaculture, the nutrient-rich deep-water can also be used in mariculture for growing marine plants. Additionally, the fresh water from the desalination process can be used for irrigation in agricultural applications [5, 6].

Hydrogen production

In conjunction with electrolysis, OTEC could produce enough hydrogen to replace fossil fuel-based energy sources. The electricity generated by OTEC systems can be used to split water into hydrogen and oxygen, providing a clean source of hydrogen fuel for various applications, including transportation and industrial processes [7].

Mineral extraction

OTEC technology can potentially be used for mineral extraction. The deep-sea water brought to the surface as part of the OTEC process is not only cold but also rich in minerals and metals. Once the cold water is brought to the surface, methods such as adsorption onto sorbents, ion exchange, and precipitation can be employed to separate and extract the minerals from the water [8, 9].

Cooling applications

OTEC technology can be used to produce cooled water to provide natural cooling for buildings, reducing the energy consumption of traditional air conditioning systems. This application has attracted interest in tropical regions where cooling demands are consistently high [10].

Climate cooling

OTEC causes cooling by transferring heat from the warm surface waters of the ocean to the colder deep waters. This process effectively removes heat from the ocean surface, which can then be radiated away from the Earth. Additionally, by cooling the ocean surface, OTEC technology can help reduce the overall temperature of the ocean, potentially impacting atmospheric temperatures as well, contributing to a cooler climate [11].

Current research and development efforts aim to reduce costs, improve efficiency, and overcome technical barriers. However, OTEC's economic potential is still being validated as it is an emerging, pre-commercial technology.

2

LITERATURE REVIEW ON OTEC ECONOMICS

OVERVIEW

This section presents a comprehensive review of the economic aspects of OTEC technology, highlighting its significance for assessing the viability and potential impact on the renewable energy landscape. The construction of large-scale offshore OTEC plants involves considerable challenges due to limited expertise, significant initial investments, and heavy reliance on government incentives. Despite its potential, OTEC struggles to compete with other renewable sources and conventional fossil fuels, impeding its widespread commercial adoption.

REVIEW OF ECONOMIC STUDIES

Langer et al. [12] published a review from academic and industrial literature between 2005 and 2019. The literature study is summarised in Table 1. Based on the critical assessment of the reviewed content, Langer et al. [12] identified seven knowledge gaps that are crucial for evaluating OTEC's economics:

1. *"Current economic analyses focus on individual plants instead of the collective economic potential within spatial boundaries;"*
2. *"Natural, location-specific influences on the real net power output are mostly omitted;"*
3. *Uncertainty about "the capital costs on both system and component level;"*
4. *Uncertainty about "operational costs and properties like useful lifetime;"*
5. *"The impact of interest rates and its selection are often not argued for in literature;"*
6. *"Technological learning is predominantly omitted in OTEC literature and if treated, it deviates from insights on technological learning;"*
7. *"Economic analyses are mostly limited to the Levelised Cost of Electricity (LCOE), while other tools like payback period and Internal Rate of Return (IRR) are neglected."*

Langer et al. [12] concluded that the current understanding of the economics of OTEC technology is significantly inhibited by a lack of empirical and operational data, primarily because commercial and near-commercial scale pilot plants are yet to be established. Consequently, most cost estimates for OTEC rely on no or historical data. The most effective way to address this issue and move beyond speculative cost assessments is through the actual deployment of OTEC plants and the transparent sharing of their economic and technical performance data.

To tackle the seven knowledge gaps identified by Langer et al. [12], the following recommendations were made:

- Deeper economic analyses of OTEC on special levels.
- Inclusion of external natural conditions.
- Stronger cooperation between industry and academia.
- Pilot plants and the publication of their operational performance.
- Finance risks of OTEC.
- Inclusion of technological learning.

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Table 1. Case studies on OTEC economics.

Literature study published by Langer et al. [12].

Ref.	Plant Location	Plant Type	CAPEX [mil.]	Plant Size [MW]	LCOE [US$(2018)/ kWh]	Interest Rate [%]	Life-time [yr]	Availability [%]	ΔT [°C]
[13]	South Korea	Land-based, Closed-cycle	0.248 US$ (N.A.)	0.02	0.38	5.0	20	91.3	21.3
[14]	Iran	N.A., Closed-cycle	2.38 US$ (N.A.)	1.6	0.094	7.5	25	N.A.	22
[15]	N.A.	Land-based, Closed-cycle	37.38, 33.37 (€(N.A.))	2.35	0.30, 0.26	9.4	30	91.3	24
[16]	Hawaii	Land-based, Closed-cycle	133.46 US$ (2011)	2.5	–	–	–	–	21.6
[17]	N.A.	Floating, Closed-cycle	123.1 € (2013)	10.0	0.23	8.0	30	95	22.0
[18]	N.A.	Floating, Closed-cycle	144-553.4 US$ (2009)	20..0	0.15-0.76	10.0	20	70-90	22.0
[19]	N.A.	Floating	110 € (N.A.)	50	0.07	8-10	30	90	70.0-180.0
[2,20]	Hawaii	Floating, Closed-cycle, Open-cycle	451, 551 (US$ (2010))	53.5, 51.25	0.209, 0.078-0.167	8.0	15	92.3	20.0
[21]	Puerto Rico	Floating, Closed-cycle	600 US$ (N.A.)	75.0	0.18	–	30	100	>20.0
[22]	Hawaii	Floating, Closed-cycle	780 US$ (2010)	100.0	0.20, 0.16	8.0, 4.2	15, 20	92.3	20.0
[23]	Nigeria	Floating, Closed-cycle	795 US$ (2015)	100.0	0.12	13.0	25	100	24.0
[24]	N.A.	Floating, Hybrid-cycle	420 US$ (N.A.)	100.0	0.08	10.0	30	N.A.	21.5
[25]	N.A.	Floating, Closed-cycle	1.400 US$ (2010)	100.0	0.22	7.4	30	95-97	N.A.
[26]	N.A.	Floating, Closed-cycle	128.8 £ (N.A.)	100.0	0.03	8.0	30	80	20.0
[27]	N.A.	Floating, Closed-cycle	420, 265 (US$ (N.A.))	100.0	–	–	–	–	–
[28]	N.A.	Floating, Closed-cycle	400 US$ (N.A.)	100.0	–	–	30	95	25.0
[29]	Hawaii, Guam, Florida	Floating, Closed-cycle	1.506, 2.494, 4.044 (US$ (2010))	100.0, 200.0, 400.0	0.20, 0.17, 0.14	4	30	92	21.4, 24.0, 20.4

In recent times, new studies that analyse the economic potential of OTEC plants have been published. Langer et al. [30] proposed a methodology for estimating the economic potential of a closed-cycle OTEC within any region, focusing on natural factors like seawater temperature differences, water depth, and distance to shore. Applied to Indonesia, the study found a potential of 0-2 GWe with an annual electricity production of 0-16 TWh. Despite the promising potential, the study acknowledges the need for optimised capital and operational expenditures to enhance economic viability, emphasizing that achieving over 90% operational availability under challenging conditions is ambitious but achievable.

An economic feasibility analysis of a 2 MW OTEC power plant in the open cycle at San Andrés Island (Colombia) was published by Herrera et al. [31]. LCOE estimates are presented for two scenarios, the first without potable water production, and the second with potable water production and sold as public service. LCOEs of 0.22 US$(2022)/kWh and of 0.26 US$(2022)/kWh have been estimated for the first and second scenarios, respectively. The results showed that the operation of an OTEC plant at San Andrés can be viable.

Aresti et al. [32] reviewed various aspects of OTEC technology, including the availability of temperature differences, technology types, and the positioning of OTEC structures, assessing their efficiency and sustainability potential. It also examines energy, economy and environment aspects, offering a critical overview of each within literature, noting energy efficiencies ranging from 2.5 to 5.3% and LCOE between 0.05 and 0.45 US$(2023)/kWh. The review discusses also barriers, technical limitations, and both past and present OTEC case studies.

Rashid et al. [33] published a study on the feasibility of OTEC plants in Bangladesh, focusing on the Bay of Bengal's marine borders. Using an advanced numerical modelling system for simulating the physical environment of the oceans, it provided precise oceanic data to evaluate the potential for sustainable energy production in response to Bangladesh's increasing power demand. The findings indicate a geographically viable option for OTEC plants, with a machine learning model forecasting an annual average power production between 103.8 and 105.8 MW. The projected LCOE is 0.164 US$(2023)/kW, with an 11-year return on investment and no greenhouse gas emissions.

Recently, the International Energy Agency's Ocean Energy Systems (IEA-OES) published a technical report authored by Vega and Martin [34]. This report offers an updated evaluation of the economic prospects for OTEC, examining its viability and potential business approaches in the context of current environmental and energy challenges. Key aspects of the report include:

- Updated capital cost estimates (US$(2023)/kWnet) based on equipment and installation quotes.
- Revised LCOE (US$(2023)/kWh) calculations considering various loan rates (see Table 2). For a 10 MW closed cycle plant-ship using standard parts, the LCOE is estimated between 0.37 US$(2023)/ kWh and 0.46 US$(2023)/kWh with concessionary loans. A semi-submersible platform in Japan costs 0.30 US$(2022)/kWh under similar loan conditions. Open cycle plant-ships, even with desalinated water credit, have a higher LCOE of 0.62 US$(2023)/kWh (commercial loans). Technological advancements and scale are expected to reduce costs. For example, future commercial facilities could see a LCOE drop to 0.26 US$(2023)/kWh for a 50 MW plant-ship under the same loan conditions.
- Comparison of new cost data with historical figures, noting significant changes such as a 35% decrease in the cost of OTEC ship-shaped vessels over the past 25 years.

The report also discusses recent policy developments, with several countries and regions including OTEC in their energy and climate transition plans.

CONCLUSION

Despite notable technical progress and grid-connected demonstration plants, OTEC faces significant economic challenges, including high initial costs and uncertainties about long-term operational expenses. Future research should focus on developing innovative financing mechanisms, risk mitigation strategies, and integrating OTEC into local and regional energy systems. Market Pull and Technology Push mechanisms are recommended to stimulate and facilitate OTEC development. Moreover, ensuring the environmental sustainability of OTEC operations is crucial for its economic and social acceptance.

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Table 2. LCOE estimates published in [34]. Open cycle plants include credit for desalinated water sales.

Abbreviations: CC (capital cost), OMR&R (levelised operation, maintenance, repair, and replacement), HXC (Heat Exchange Company), where HXC-A refers to company A and HXC-B to company B.

Plant Type	Capital Cost [US$(2023)/kW]	OMR&R [% CC]	LCOE [US$(2023)/kWh], 8% - 15 years commercial loan	LCOE [US$(2023)/kWh], 2.5% - 20 years concessionary loan
10 MW Closed Cycle (w/ HXC-A)	27.012	5.5%	0.615	0.462
10 MW Closed Cycle (w/ HXC-B)	21.606	5.5%	0.492	0.370
10 MW Closed Cycle 1st in Class Japan Data	32.169	2.75 US$(2023) MM/yr	0.506	0.301
10 MW Closed Cycle Commercial Japan Data	27.700	2.24 US$(2023) MM/yr	0.356	0.214
10 MW Open Cycle	33.962	5.5%	0.618	0.424
50 MW Closed Cycle (w/ HXC-A)	16.578	5.5%	0.378	0.284
50 MW Closed Cycle (w/ HXC-B)	11.223	5.5%	0.256	0.192
50 MW Open Cycle	22.722	5.5%	0.362	0.233
100 MW Closed Cycle (w/ HXC-A)	13.023	5.5%	0.297	
100 MW Closed Cycle (w/ HXC-B)	8.817	5.5%	0.201	

3

UPSCALING SCENARIOS

INTRODUCTION TO SCALABILITY CHALLENGES

Scalability is a critical aspect of transitioning OTEC technology from experimental or pilot projects to full-scale commercial operations. However, there are limited documented scenarios on successful upscaling, which poses significant challenges for stakeholders aiming to understand and overcome the barriers to commercial viability. However, few studies have documented scenarios related to upscaling.

EMPIRICAL STUDIES AND SIMULATIONS IN LITERATURE

Vega [35] reported that OTEC plants have a commercial future in floating plants of approximately 100 MW capacity for industrialised countries and smaller plants for Small Island Developing States (SIDS). However, the lack of operational data has been identified to be a major challenge to commercial development. According to Vega [35] a scaled version of a commercial size plant must be designed and operated to establish the life cycles of major components and yearly production rates prior to commercialisation. A 1/5 scaled version of a 25 MW module was proposed as an appropriate size, corresponding to a size considered viable for SIDS.

Martel et al. [29] estimated the costs of OTEC power based on 100 MW, 200 MW and 400 MW plants. The report examined the capital, operations, and sustainment expenses associated with OTEC to assess the long-term operation of the OTEC plants to supply energy for 30 or more years while operating in harsh environmental conditions. The report suggested that it is conceivable that within 20 years of deployment of the first commercial OTEC plant, LCOE values can be driven well below 10 cents (2012) per kWh.

Langer et al. [36] discussed different scenarios for the upscaling of OTEC from small pilots to large-scale plants using a simulation model, which includes location-specific data such as electricity demand, electricity tariff, and investment costs as a function of distance to shore and sea-water temperature difference, as well as the inclusion of a learning rate for investment costs and cost of finance. Upscaling is simulated for Indonesia, but discussed globally, since they are relevant for other areas around the world. The results revealed the evolution of LCOE over time, starting from an initial range of 0.339-0.507 US$(2018)/kWh for the first pioneer plant to 0.062-0.069 US$(2018)/kWh by 2050 as the technology reached maturity. The study showed that OTEC has the potential to contribute significantly to the descarbonisation of global energy systems, with up to 45 GW in Indonesia. However, large-scale OTEC

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will probably only be relevant for an exclusive group of sufficiently large countries in the tropics and subtropics.

Additionally, Langer et al. [37] analysed the impact of system size and costs for small-scale, medium-scale, and large-scale systems of 4.4 MW, 80 MW and 126 MW, respectively. From this study, it has been determined that larger OTEC systems designed with a "bigger-is-better" approach offer significant advantages. These systems not only produce the largest and most continuous power output, but also enhance economic resilience against unplanned downtimes, potentially reducing investment risks. Despite higher initial costs, in regions with low to moderate seasonal temperature variations, the "bigger-is-better" systems can achieve the lowest LCOE due to their higher excess electricity production. However, in areas with significant temperature fluctuations, the increased costs do not justify the benefits, and slightly less conservative designs yield the lowest LCOE.

BARRIERS TO UPSCALING

According to the available literature [33, 38], there are several limitations of OTEC technology that need to be addressed for upscaling:

High Construction Costs

The substantial initial investment required makes both governments and private investors hesitant, though venture capital funds have started to invest in OTEC companies.

Suitable Oceanic Conditions

The availability of appropriate conditions for OTEC can limit potential sites for upscaling in certain regions.

Economic Feasibility

In areas with low energy demand, the LCOE increases, making large-scale OTEC deployments unsuitable.

Environmental Concerns

Issues such as ocean thermal degradation and the potential relocation of toxic materials must be addressed, although environmental studies have shown these risks can be managed using existing technology.

Technological Learning and Cost Assumptions

Current public studies often lack realistic technological learning curves and cost assumptions, which are essential for accurate forecasting and planning. Nonetheless, private sector OTEC developers have produced investible business plans and raised finance on the promise of nearer term breakthroughs in economics.

RECOMMENDATIONS

To advance the scalability of OTEC technology, a focused effort on collecting empirical data and conducting comprehensive, commercial-scale pilot projects is essential. Stakeholders, including governments, industry leaders, and academia, must collaborate internationally to overcome the noted barriers. Investing in technological innovation and sharing operational data transparently will be crucial for realising the full potential of OTEC as a cornerstone of renewable energy strategies globally.

4

MAJOR COMPONENTS AND SUBSYSTEMS OF AN OTEC PLANT

The design and efficiency of an OTEC plant depend on several essential parameters. Understanding and optimising these parameters are crucial for the successful implementation and operation of OTEC systems. In November 2009, NOAA's Office of Ocean and Coastal Resource Management (OCRM), in partnership with the Coastal Response Research Center (CRRC), hosted a workshop aimed at gathering qualitative information to focus on the state-of-art of OTEC components and technical readiness of the technology to be scaled to a size greater than 100 MW [39]. This collaborative effort identified seven key components as critical bottlenecks for the advancement of OTEC technology. These components are:

Platforms

The workshop identified three platform designs, semi-submersible, spar and mono-hull, as the most feasible for OTEC applications, all of which are already proven in industries like offshore oil and wind, with no significant new challenges in manufacturing, operation, or deployment for OTEC use. Semi-submersibles are built using standard offshore rig processes, though spar platforms have a limited number of skilled contractors compared to semi-submersibles and mono-hulls. Mono-hulls are constructed using Floating, Production, Storage, and Off-loading (FPSO) units. Spar platforms, requiring deep-water work, pose the greatest installation challenges and are more complex to operate. However, they offer advantages for cold water pipe attachment due to minimal motion at the joint, despite relocation challenges that necessitate disassembly and reassembly. Operation and maintenance procedures are well-established across all platform types. Decommissioning processes are also straightforward, mirroring practices from other sectors. The primary research and development goals for OTEC platforms focus on enhancing efficiency and reducing costs through improved manufacturing and deployment methods. As OTEC platform technology is adapted from other fields, specific standards for OTEC applications may be developed to ensure optimal performance and economic viability. Beyond the workshop, attempts to examine the seakeeping capabilities of floating OTEC platforms have been made. Barr et al. [40] applied analytical methods to assess the OTEC seakeeping performance. Then, Kowalyshyn and Barr [41] conducted an assessment on an actual example of seakeeping performance. Subsequently, Ertekin et al. [42] investigated the platform hydrodynamics to ensure the device operation within designated regions.

Mooring system

Assuming OTEC platforms align with those used in the offshore oil industry, mooring technology is well-developed and proven in harsh environments. The focus is on optimising the mooring system for economic viability in specific deployments. Mooring

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technology should be capable of reaching depths up to 3000 m. Therefore, mooring system design, fabrication, and construction require minimal customisation, although complexity increases with platform size and seabed variability. Deployment and decommissioning are straightforward, with potential minor equipment modifications. OTEC platforms, positioned in deep waters, face unique design challenges due to their location and exposure to severe sea conditions, including the need for disconnection and recovery during extreme storms. Therefore, research areas include adapting standards for OTEC, mooring on sloped seabeds, minimal equipment techniques for installation, anchoring in volcanic rock, and innovative designs adapted to OTEC needs. Complementing the workshop, an important component is the anchoring. One study by Atturio et al. [43] has been identified for the selection of the anchoring system for OTEC platforms.

Platform-pipe interface

The workshop concluded that while technology exists for interfaces suitable for smaller diameter cold water pipes, it is not yet available for larger scales needed for above 100 MWe facilities. Three main designs are recognised: flex pipe with a surface buoy, a fixed interface, and a gimbal interface, which are an adaptation from the offshore oil industry practices. Developing a platform-pipe interface for larger OTEC plants will require extensive testing and modelling. Fixed and gimbaled interfaces are simpler to design and produce compared to the more complex flex interfaces. Scalability is highest for fixed interfaces, followed by the gimbaled. Flex interfaces may not be suitable for above 100 MWe plants due to cold water pipes size constraints. Key challenges include the lack of experience with interfaces for cold water piper larger than 1m in diameter and the need for significant design and fabrication efforts to develop a robust interface capable of handling the open ocean forces and enabling coupling/decoupling of the cold water pipe [44].

Heat exchangers

For OTEC, the most suited heat exchanger shapes are shell and tube, typically constructed of titanium, carbon steel, stainless steel, copper-nickel, or aluminium, plate-and-frame, constructed of stainless or titanium, and aluminium plate-fin, fabricated with brazed aluminium. Shell and tube exchangers are labour intensive to manufacture, but relatively low-cost to integrate into OTEC facilities. Scalability to above 100 MWe facilities is feasible. Plate-and-frame exchangers have automated manufacturing processes but present challenges in installation due to complex piping and expensive valving. Plate-and-frame exchangers offer less flexibility and limited scalability for OTEC applications in comparison to shell and tube exchangers. Aluminium plate-fin exchangers have a modular design similar to shell and tube, but with lower output per module. Aluminium plat-fin exchangers have the ability to be scaled in modules. Challenges across all exchanger types include managing the environmental risks of working fluid leaks, biofouling, and the limited economic incentive for manufactures to optimise exchanger designs for the modest temperature differential in OTEC applications.

Pumps and turbines

In comparison with other components of OTEC plants, pump and turbine technologies are the most technically advanced and ready to use. The petroleum industry's extensive experience with these technologies in harsh, offshore environments has proven their reliability and effectiveness for large-scale MWe production. OTEC facilities require efficient axial flow impeller pumps, which are commercially available and capable of handling the significant volumes of water needed for large MWe facilities. These pumps boast high efficiency rates and can be easily integrated into large-scale operations. According to Vega [45], a 100 MWe facility would require pumps capable of moving approximately 200 m^3/s of cold water and 400 m^3/s of hot water. The turbines and pumps necessary for OTEC applications are readily available, with materials and designs that suit the specific needs of OTEC systems. Modular designs and established manufacturing practices support the scalability and integration of these components into OTEC platforms. Maintenance routines for turbines and pumps are well established, minimising operational risks and ensuring long-term reliability. Overall, the current efficiency of OTEC turbines and pumps is high, and further improvements in efficiency could enhance the net power output of OTEC facilities. In addition, as high-power generation systems are rare, the high-power turbine for OTEC is also one of the future development tasks [46]. Complementing the workshop, numerical studies to enhance turbine efficiency have been carried out. Some examples are: Nithesh and Chatterjee [47], Nithesh and Smad [48], and Chen et al [49]. These studies are beneficial in designing turbines for OTEC systems.

Power cable

While the technology for power cable systems suitable for OTEC facilities exists, several limitations impact their use. Key challenges include the limited selection of high-voltage cables (above 500 kV) and the necessity for custom designs for OTEC plants exceeding 10 MWe. For distances under 20 miles, AC cables are preferred. However, for longer distances, DC cables may be considered to minimise transmission losses, despite the inefficiency caused by AC-DC conversion. For cables under 500 kV, off-the-shelf solutions or minimally customised designs are available. However, for cable exceeding 500 kV, no commercial product exists and significant effort would be required to design and manufacture an appropriate cable. Scaling the power cable system for a 100 MWe OTEC facility presents challenges due to capacity limitations. A 10 MWe plant cable type and design will not be adequate for a 100 MWe facility, necessitating a completely new design. Challenges and risks include the engineering and technological difficulties associated with the cable termination interface, especially for larger OTEC plants, which may experience increased fatigue and stress. Deep water locations pose additional challenges due to hydrostatic pressure.

Cold water pipe

Different materials have been proposed for the cold water pipe, including steel, aluminium, rubber, concrete, plastic, and fibre-reinforced composites. The construction and deployment of cold water pipes for facilities up to 10 MWe are well understood, with methods validated for pipes around 7 metres in diameter, though scaling up to 100 MWe (approximately 10 metres in diameter) remains untested. Suspending a long and wide pipe from an OTEC plant involves complex engineering challenges, including large loads on the platform-pipe coupling and installation logistics. These difficulties were significant obstacles to OTEC development in the eighties. The dynamic loading from ocean currents poses risks of failure on the pipe and its connection joints [50-52]. Research into vortex-shedding-induced dynamic loads has motivated the development of various flexible designs for the plant-to-pipe joint to address these issues [53, 54]. The lack of experience with larger cold water pipes is a primary barrier for scaling up to 100 MWe facilities.

5

MAIN CHALLENGES IN OTEC TECHNOLOGY

OTEC technology offers a promising solution to generate renewable energy by exploiting the temperature difference between warmer surface water and cooler deep seawater.

Despite its potential, the technology encounters significant technical, environmental, and economic challenges that need to be addressed.

TECHNICAL CHALLENGES

Scaling up [36, 55]

While there have been successful small-scale OTEC projects, scaling up to commercial levels poses technical and logistical challenges. Larger systems require more robust land-based plants or floating platforms. In the case of a floating platform, a deep-water mooring system is required. In addition, the risers must extend between 750 and 1500 metres below the sea surface.

Efficiency of cycles and components [56]

OTEC systems have relatively low thermal efficiency due to the small temperature difference between the surface and deep waters. In combination to the small temperature difference, the water flow rates have to be very large, and the heat exchangers must be as efficient as possible.

Designing resilient risers [18]

The installation of risers has posed a long-term challenge that has long-hampered OTEC's commercial feasibility. Dynamic loading of the riser from ocean currents may potentially lead the riser or connection joint to failure. Additionally, there have been many studies of potential problems from vortex-shedding-induced vibrations.

Larger seawater pumps and pipping systems [57]

The small temperature difference necessitates large volumes of water, which requires large seawater pumps and pipping systems.

Material and design limitations [58, 59]

Developing materials and components, such as heat exchangers, that can withstand corrosive seawater, biofouling, and the operational stresses of deep and surface water is challenging. These materials must also be cost-effective and durable.

ENVIRONMENTAL CHALLENGES

Lowering surface temperature [25]
Discussions have highlighted concerns about whether the cold water discharged by OTEC plants could change the temperature of surface ocean water near the plants and potentially harm marine life. Additionally, OTEC has the potential to positively affect hurricane formation, as hurricanes, which develop in warmer waters, weaken when they encounter cooler surface temperatures.

Water quality changes [60]
Nutrient-rich water discharged at the ocean's surface can lead to changes in local concentrations of nutrients and dissolved gases. These processes may affect marine life and the dynamics of the ecosystems.

Platform presence [61]
The presence of OTEC platforms may cause organism attraction or avoidance, and mooring lines may cause entanglements.

Acoustical and electromagnetic field [61]
Noise from plant operation may have an impact on marine mammal echolocation and communication. Additionally, the electromagnetic field may interfere with marine organisms that use electric fields for prey detection.

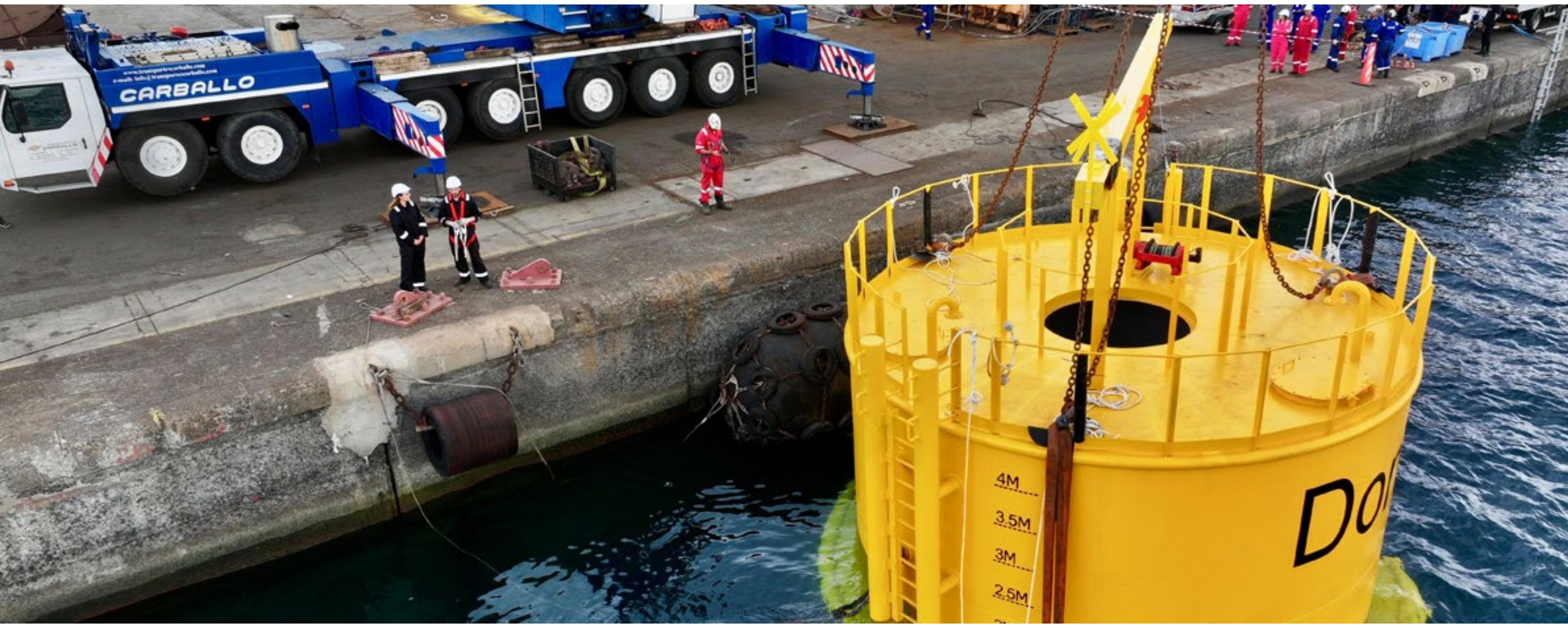
ECONOMIC CHALLENGES

High costs [57]
At present, OTEC technology is costly. There are many utilisation ways of ocean thermal energy, such as power generation, refrigeration, and desalination, but the costs are still high.

Limited locations [57]
Large-scale OTEC will probably only be relevant for an exclusive group of countries in the tropics and subtropics. This geographical limitation can restrict potential markets and increase costs for sites that are not ideally situated.

Competitiveness [62]
With the decreasing costs of other renewable energy technologies, such as solar and wind, OTEC must demonstrate cost-competitive LCOE to attract investment.

Lack of comprehensive projects [25]
Although some studies have been addressed specific challenges with OTEC implementation, there is yet no single project that extensively addresses the full range of challenges.



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6

MITIGATIONS FOR CHALLENGES OF OTEC TECHNOLOGY

To address the main technical, environmental and economic challenges identified in OTEC technology, this section explores targeted mitigation strategies to overcome these obstacles.

TECHNICAL CHALLENGES

Scaling up

Scaling up OTEC systems requires modular designs that allow for gradual scaling, which mitigates risks associated with large, single-stage installations. Floating platforms with advanced mooring systems, like those used in offshore oil and gas, can stabilise structures in deep water conditions. For floating installations, floating barges, semi-submersible and tension-leg platforms are effective solutions [63]. Research into flexible risers, similar to those used in subsea oil extraction, would help extend OTEC risers deeper into the ocean, adapting to various depths with reduced stress on connection joints [8].

Efficiency of cycles and components [64, 65]

To improve the efficiency of cycles and components, high-capacity pumps and optimised heat exchangers can help capture this difference more effectively. Research shows that the use of efficient, large-volume pumps can reduce energy loss and increase overall system performance in marine applications.

Designing resilient risers [66]

The resilient design of risers is essential since OTEC risers face dynamic ocean loading from currents, jeopardising their stability and lifespan. Flexible materials, like high-density polyethylene (HDPE), can resist these loads and minimise failures caused by vortex-induced vibrations. Vortex suppression techniques, such as helical strakes and fairings, are already successful in offshore oil applications and can be adapted to strengthen OTEC risers.

Larger seawater pumps and pipping systems

Large-volume seawater pumps that maintain flow rates without excessive energy demand are essential due to OTEC's reliance on substantial water volumes. Research into high-efficiency pumps and robust, corrosion-resistant materials, like titanium alloys or polyethylene-lined steel, can significantly reduce maintenance needs and operational costs. Lessons from desalination suggest that advanced piping systems can help manage biofouling and scaling, with options like self-cleaning coatings and routine mechanical cleaning solutions extending pipe lifespan.

Material and design limitations

Material and design limitations are significant for any

OTEC development. Seawater corrosion, biofouling, and pressure differentials create challenges for component durability. Solutions include corrosion-resistant alloys, anti-fouling coatings, and hybrid materials, like fibre-reinforced polymers, which can withstand harsh marine conditions while remaining cost-effective. Collaborative development with material scientists can lead to affordable, high-durability heat exchangers and risers, improving system lifespan and reducing long-term costs.

ENVIRONMENTAL CHALLENGES

Lowering surface temperature [67, 68]

Cold water discharged by OTEC systems can disrupt local surface temperatures, potentially affecting marine ecosystems. Optimal placement of discharge pipes at depths where the water temperature is similar to that of the discharged water helps minimise thermal impacts on surface ecosystems. Modelling techniques assist in determining the ideal depth for each location, with studies showing that careful discharge design can help reduce adverse effects on marine environments.

Water quality changes [69]

Nutrient-rich deep water discharged at the surface may alter local marine ecosystems. Depth-controlled discharge methods, such as using mid-depth outlets rather than surface release, can reduce nutrient concentration changes. Bio-monitoring around OTEC facilities allows for tracking of ecosystem changes and adjustment of discharge strategies as needed to minimise environmental impacts.

Platform presence

The presence of OTEC platforms may attract or repel certain marine organisms, leading to ecological disturbances. Platform designs that incorporate non-reflective, anti-fouling coatings reduce organism attraction, while adjusting the spacing and tension in mooring lines can lower the risk of entanglement for marine mammals. Research into marine species' attraction and avoidance behaviours informs platform design, further mitigating ecosystem disruption.

Acoustical and electromagnetic field [70]

Noise from pumps and turbines can interfere with marine mammal echolocation, making sound reduction important. Installing noise dampeners and using quieter equipment helps mitigate acoustic impacts, a strategy proven effective in offshore wind and subsea industries. Electromagnetic shielding in power transmission lines reduces interference with marine organisms that use electric fields for navigation, a practice used in other offshore applications.

ECONOMIC CHALLENGES

High costs [71-73]

High initial costs make OTEC less economically viable, but combining power generation with other applications, such as desalination or cold-water aquaculture, creates diverse revenue streams and reduces the need for subsidies. Dual-purpose OTEC designs broaden investment appeal by providing multiple benefits.

Limited locations [74]

Leveraging government subsidies, international grants, and co-financing from environmental organisations supports early projects, making costs more manageable for island and coastal nations.

Competitiveness [12]

To improve OTEC's competitiveness in the renewable energy market, it is essential to reduce the LCOE. Technological advancements, particularly in heat exchangers, pumps, and materials, help lower LCOE, allowing OTEC to compete more favourably with other renewable sources like wind and solar. Emphasising OTEC's unique ability to provide base-load power can also attract investors seeking stable energy sources.

Lack of comprehensive projects

The lack of comprehensive projects addressing all of OTEC's challenges is a limitation, but targeted pilot projects that integrate energy generation, environmental safeguards, and economic assessments can serve as valuable proofs of concept. Partnerships among governments, academia, and the private sector are essential for these pilots, and public awareness campaigns could further build support for OTEC, leading to funding and political backing for future projects.

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This review underscores the significant potential of OTEC technology as a sustainable and renewable energy source, particularly beneficial for island nations and coastal regions where thermal gradients are favourable.

7

CONCLUDING REMARKS

This review underscores the significant potential of OTEC technology as a sustainable and renewable energy source, particularly beneficial for island nations and coastal regions where thermal gradients are favourable. OTEC's journey from early 20th-century experiments to the development of both open and closed-cycle systems highlights its evolutionary path. Despite these advancements, considerable challenges hinder its broad commercial deployment.

CHALLENGES AND POTENTIAL

The path to realizing OTEC's full potential is fraught with hurdles, including high initial costs, the need for extensive infrastructure, and environmental challenges specific to marine operations. Yet, the diverse applications of OTEC—ranging from electricity generation and water desalination to aquaculture and beyond—illustrate its multifaceted benefits.

STRATEGIC DIRECTIONS FOR RESEARCH AND DEVELOPMENT

Addressing the technical and economic challenges identified requires targeted research and development efforts. Priorities include enhancing component efficiency, leveraging innovative financing to reduce costs, and adopting risk mitigation strategies. Integration of OTEC within local and regional energy frameworks, supported by conducive policies, is critical. Additionally, environmental sustainability must be a core focus to ensure the long-term viability and acceptance of OTEC systems.

CALL TO ACTION

The future of OTEC demands a collaborative strategy involving government, industry, academia, and international bodies. Together, these stakeholders must drive technological innovations, support pilot projects, and foster transparent sharing of data. This collective effort is essential to navigate the complexities of OTEC technology and secure its place as a cornerstone of global renewable energy solutions.

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8

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