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Harnessing the Ocean's depths: SWAC and OTEC for sustainable cooling and power - A review of technologies, applications and challenges

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ABSTRACT

This review provides an in-depth analysis of deep ocean water (DOW) energy systems, highlighting their potential to address the growing demand for cooling and energy sustainability while reducing dependence on fossil fuels. This article highlights the urgent need for sustainable alternatives and explores key technologies such as Sea Water Air Conditioning (SWAC) and Ocean Thermal Energy Conversion (OTEC), including applications like desalination and aquaculture systems. This review evaluates the practical applications, successes, and challenges of these technologies through global case studies and real-world implementations. Special attention is given to environmental and social considerations, including impacts on marine ecosystems and socio-economic implications. Through a comprehensive synthesis of findings, this review identifies both opportunities and barriers to the adoption of deep ocean water energy systems, emphasizing their crucial role in climate change mitigation and sustainable development. In addition to sustainability, key strengths of this review include its interdisciplinary perspective and its reliance on real-world case studies to evaluate the practical viability of these systems. It offers valuable insights to guide future research and implementation strategies for these promising energy solutions.

Nomenclature

ASHP	Air Source Heat Pump
BWIS	Beach Well Infiltration System
CAPEX	Capital Expenditures
COP	Coefficient of Performance
CW/SW	Chilled Water/Sea Water
DOW	Deep Ocean Water
e	Electrical
EONS	Electrodeposited Oxy-Nitriding Steel
HCHE	Helical Coil Heat Exchanger
HEX	Heat Exchanger
LCOE	Levelized Cost of Energy
LSC	Lake Source Cooling
OPEX	Operational Expenditures
ORC	Organic Rankine Cycle
OTEC	Ocean Thermal Energy Conversion
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SCOP	Seasonal Coefficient of Performance
SHEX	Solution Heat Exchanger
SWAC	Sea Water Air Conditioning
SWHP	Sea Water Heat Pump
t	Thermal

In the nomenclature, the subscript e is used for electrical quantities and t for thermal quantities. This distinction was adopted to avoid confusion between the cooling power delivered by SWAC systems, the electricity produced by OTEC plants, and the electricity consumed by SWAC installations.

1. Introduction

The impacts of climate change are becoming increasingly evident, with the rising demand for cooling solutions worldwide being one of the unavoidable consequences of global warming according to the IPCC [1]. As air temperature gets higher, so does the need for air conditioning

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(AC) in both developed and developing countries, especially in hot and humid regions with expanding demography [2]. This trend is detailed by the International Energy Agency in a report entitled “The Future of Cooling”. Energy consumption for cooling purposes has tripled between 1990 and 2016, making it the most increasing energy demand sector worldwide, and it will continue to rise significantly until 2050. Electrical grids are strained by such rapid increases, especially in insular territories, and the surge in AC usage has led to a threefold increase in carbon dioxide emissions, reaching 1130 million tons per year in 2016 [3]. The use of HFCs in some conventional AC systems is also a threat since they are potent greenhouse gas [4]. Moreover, the impact of climate change not only raises median temperatures but also affects temperature variance, necessitating the consideration of future heatwave risks in building design and cooling solutions [5].

In response to this escalating energy demand and its associated environmental consequences, an urgent need arises for resilient cooling strategies, as defined by the IEA’s annex 80 [6], and other sustainable alternatives. Among these alternatives to conventional air conditioning systems, Sea Water Air Conditioning (SWAC) technology is a promising solution for coastal regions with access to cold Deep Ocean Water (DOW). SWAC’s efficiency has been demonstrated through a two-year experimental study on the Tetiaroa SWAC installation [7] operating in real conditions. The Seasonal Coefficient of Performance (SCOP) reached 25.4 for the studied time period [8], which is about 7 times higher than the conventional split system [3].

Yet, the significance of ocean water extends far beyond cooling solutions alone, the ocean holds significant potential to meet global energy demands with oceans covering about 70 % of the Earth’s surface, they act as vast collectors of thermal energy. There is an immense energy potential with global ocean energy development capability estimated at 337 GW, capable of yielding over 885 TWh of electricity production [9]. However, despite this vast potential, marine power production capacity remains relatively modest [10], with only a very limited number of deep ocean water energy systems deployed to date across all categories.

Tropical regions have even greater benefits in developing deep ocean water energy systems as their insularity makes them especially dependent on fossil fuels for cooling needs, electricity production, drinking water (with seawater desalination) and food production (with aquaculture). Harnessing deep ocean water, whether it’s for cooling purposes with SWAC technology or for electricity needs with Ocean Thermal Energy Conversion (OTEC), not only offers a low-carbon energy source but is also a way to mitigate our reliance on fossil fuels. DOW energy systems can also be used for desalination, especially open-cycle OTEC, which are less energy consuming than typical desalination systems [11]. Furthermore, the seawater reject can be valorized with aquaculture systems.

This potential is already being exploited in several countries have already implemented systems that harness naturally cold water sources for cooling or electricity production. French Polynesia has deployed deep ocean water-based systems for large-scale cooling in hotels and hospitals. Similarly, countries such as Switzerland, Canada, and the United States have adopted lake-source cooling systems, which rely on the same principle but use cold freshwater from deep lakes. In parallel, Hawaii, Japan, and South Korea operate pilot-scale OTEC plants for electricity generation, demonstrating the potential of thermal gradients in ocean water as a renewable energy source.

In light of these interconnected factors – escalating cooling needs, environmental imperatives, and the untapped potential of deep ocean energy – the exploration of deep ocean water energy systems emerges as a compelling imperative. Despite the growing number of studies on SWAC and OTEC technologies, the existing literature remains fragmented. Many publications focus narrowly on technical performance or economic feasibility, often neglecting environmental impacts, social acceptance, and the synergies between cooling, electricity, desalination, and aquaculture. Furthermore, comprehensive reviews that analyze both implemented projects and theoretical studies across diverse geographies are rare. This fragmented perspective limits the development of integrated, scalable solutions adapted to the specific challenges of insular and coastal regions.

This review aims to investigate the various facets of deep ocean water energy technologies, their applications, and the multiple benefits they offer, particularly for insular territories struggling with the dual challenge of cooling demand and energy sustainability. It also addresses a critical gap in the literature by providing a comprehensive and interdisciplinary synthesis that includes SWAC and OTEC technologies, as well as their integration with desalination and aquaculture systems. Whereas previous studies often focus on isolated technical or economic dimensions, this review incorporates real-world deployments, feasibility assessments, and socio-environmental impacts. It is intended to serve as a reference point for researchers, policymakers, and practitioners seeking sustainable and resilient energy solutions adapted to coastal and island contexts.

The following sections of this paper are arranged as follows: First, Section 2 describes the methodology used to conduct this review. Sections 3 and 4 detail the main energy systems utilizing deep ocean water, namely SWAC and OTEC, describing their general principles, theoretical approach, and a review of case studies and current implementations documented in the literature. Environmental and social impacts, including the effects on marine ecosystems and public perception of these technologies, are addressed in Section 5. Other potential applications of deep ocean water resources, such as desalination and aquaculture, are explored in Section 6. Section 7 presents a comparative analysis of SWAC and OTEC with conventional and renewable alternatives. Finally, Section 8 presents a conclusion and identifies development prospects for DOW energy systems.

2. Methodology

This review was conducted using a semi-structured approach, combining targeted keyword-based searches with a snowball sampling method to identify relevant literature on deep ocean water energy systems. Major scientific databases including Scopus, Web of Science, ScienceDirect, SpringerLink, and the SciSpace AI-powered tool, covering the period from 2000 to early 2024.

Keyword combinations were adapted to each topic, including: “Sea Water Air Conditioning”, “SWAC”, “Ocean Thermal Energy Conversion”, “OTEC”, “deep ocean water”, “DOW”, “Lake Source Cooling”, “LSC”, “Lake Water Air Conditioning”, “seawater cooling”, “artificial upwelling”, “marine energy environmental impact”, “deep seawater desalination”, “open OTEC”, “deep seawater aquaculture”. In addition to keyword searches, a snowball sampling strategy was used to identify additional relevant references by reviewing the bibliographies of key papers and tracking newer publications that cited them.

Selection criteria focused on relevance to deep ocean water-based technologies, including both direct cooling systems (e.g., free cooling using seawater or lake water) and indirect systems using seawater as a heat sink for conventional chillers or heat pumps. We included: (i) Case studies of operational or pre-feasibility SWAC systems, (ii) Case studies of operational OTEC facilities, (iii) Theoretical studies on complementary valorizations, such as desalination and aquaculture, (iv) Research assessing the environmental impacts of deep ocean water energy systems.

The overall identification, screening, eligibility assessment, and inclusion process is summarized in Fig. 1, which presents the PRISMA flow diagram of the literature search and selection process. In total, approximately 150 documents were screened, and around 80 were retained for detailed review and citation in this article.

3. Sea Water Air Conditioning (SWAC)

In this section on SWAC, we will consider all systems that utilize water for cooling purposes, whether drawn from the sea or a lake, as the

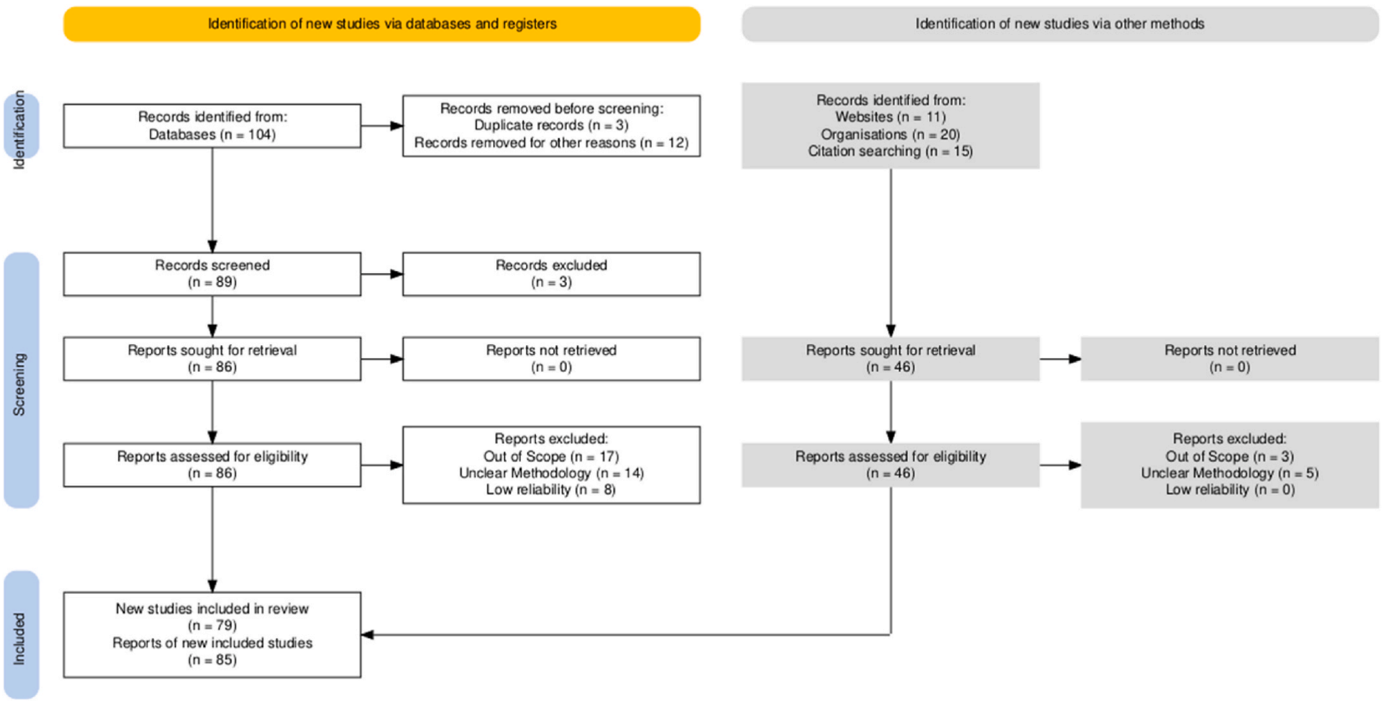

Fig. 1. PRISMA 2020 flow diagram of the literature search and selection process for studies on deep ocean water energy systems [12].

fundamental principle remains the same. These systems can operate either using cold water directly (known as free cooling) or as a heat sink for conventional cooling technologies, such as heat pumps. To distinguish between different configurations, we will use the term "Deep SWAC" to refer to free cooling systems that draw water from great depths, while "Shallow SWAC" will describe systems that use surface water to assist heat pumps or conventional chiller units (Fig. 2).

3.1. Operating principle: "deep SWAC"

The SWAC (Sea Water Air Conditioning) technology involves pumping naturally cold seawater from deep depths through a pipeline anchored to the seabed. The deep water passes through a heat exchanger to transfer its cooling energy to a closed-loop chilled water network, which ensures the distribution of cold air throughout the buildings to be air-conditioned. This process bypasses the limitations of conventional thermodynamic cycles, as it relies on the transport of cold fluid in a liquid phase rather than on the heat pumping from a cold source to a hot source, whose performance is constrained by Carnot's efficiency.

The typical SWAC system is illustrated in the diagram below (Fig. 3) and consists of three main components: (i) the primary sea water (SW) loop includes an intake pipeline that extends down to approximately 1000 m in depth and a discharge pipeline around 20–30 m deep. The seawater enters at a temperature of around 5–7 °C and is discharged at a temperature between 11 °C and 13 °C [13]. The discharge point is typically designed to release seawater at a temperature close to that of the surrounding environment to minimize impacts on marine flora and fauna. However, this discharge temperature is not subject to specific regulations in French Polynesia for existing installations. (ii) the secondary chilled water (CW) loop serves as the cooling distribution network within the building. The CW temperature is generally set at 7 °C for supply and 12 °C for return. (iii) the technical room houses one or more pumps for each of the two loops, as well as heat exchangers that transfer cooling energy from the SW loop to the CW loop.

3.2. Theoretical approach

Studies on SWAC technology in scientific literature focus on various aspects, including: (i) the materials used for the heat exchanger, (ii) system optimization, (iii) coupling with other systems, (iv) best localization of SWAC systems [14–16].

3.2.1. Heat exchangers

The main component of the SWAC process is the heat exchanger located in the technical room, which enables the transfer of cooling energy from the SW loop to the CW loop. Heat exchangers are typically made of titanium plates that exhibit diminished corrosion when exposed to seawater, though aluminum is also a viable option.

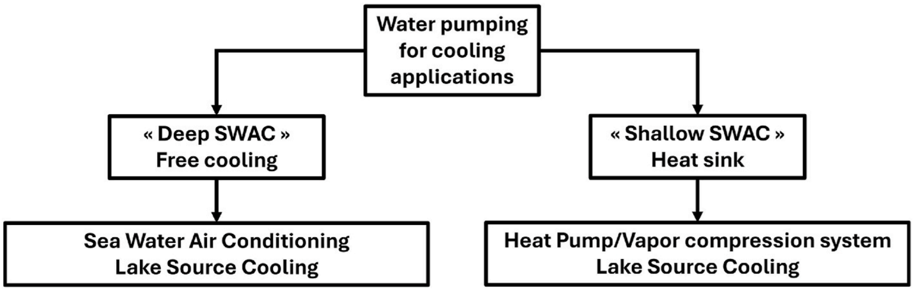

Fig. 2. Classification of Water-Based Cooling Systems (Deep SWAC vs. Shallow SWAC).

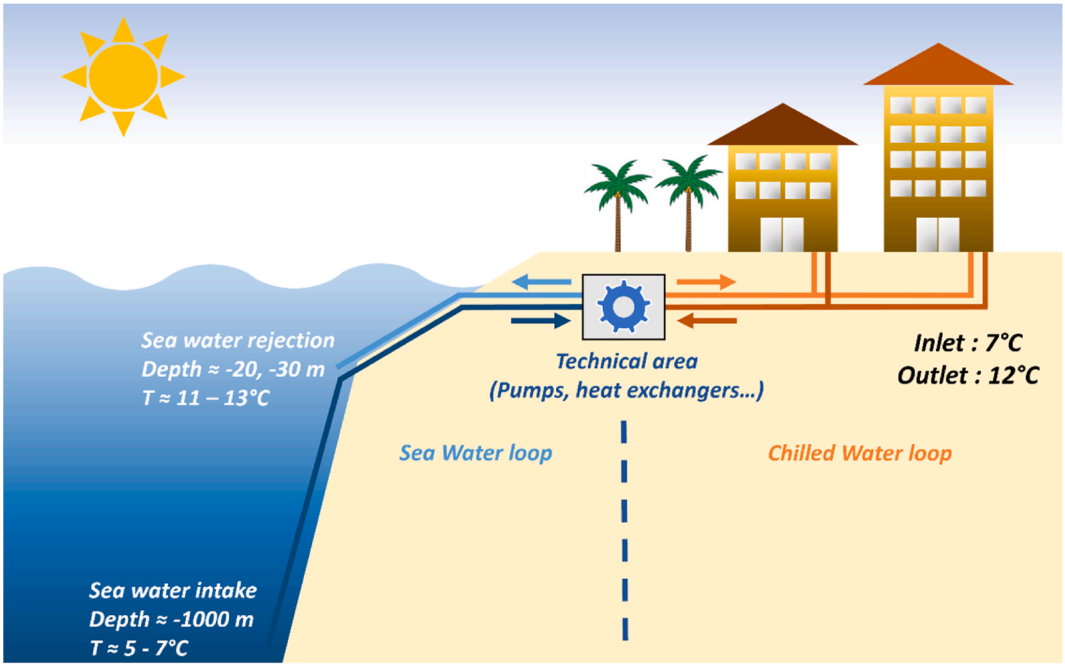

Fig. 3. Typical operating principle of deep SWAC installation [7].

An alternative to titanium, using steel plates treated with electro-deposited oxynitriding (EONS), has been proposed by Kim et al. [17]. In this study, four different plate materials were compared: titanium, stainless steel with and without a "diamond-like" coating, and electro-deposited oxynitrided steel. The results showed that EONS plates exhibit good corrosion resistance, with a lifespan of more than 13.4 years, and improved heat transfer performance compared to titanium plates. This substitution could reduce the production costs of heat exchangers, making SWAC systems more economically viable. The economic analysis revealed that for EONS plates to be competitive, their production cost must be less than 46.5 % of that of titanium plates, considering the lifespan of 13.9 years for EONS plates compared to 30 years for titanium plates. This cost reduction is currently achievable with mass production technologies [17].

Liu et al. considered a system with a closed primary loop. This loop includes a submerged coil-shaped heat exchanger placed on the ocean floor and a surface heat exchanger [18]. This design is presented as a solution to the corrosion issues caused by seawater on primary pipelines and the potential disruptions to the marine ecosystem resulting from seawater discharge. The authors analyze the performance of closed-loop SWAC systems under different operating conditions through numerical simulations. Their results show that increasing the length and diameter of the pipes, as well as the flow velocity, improves heat exchange capacity but also increases resistance losses. They propose an optimization of pipe diameters and flow velocity to maximize thermal efficiency while minimizing costs and pressure losses. Since the system is closed, there is no water discharge, but heat is released into the surrounding deep-water environment, which may have a potential thermal impact on the ecosystem.

3.2.2. *System optimization*

SWAC optimization has most often been studied for open primary loop operation. Hernández-Romero et al. used a linear simulation model optimized using a MILP (Mixed-Integer Linear Programming) algorithm, where objective functions and constraints are linear functions. This approach has demonstrated that exclusive use of SWAC can reduce CO_2 emissions by up to 91.3 % compared to conventional air conditioning systems [19]. The authors of this article extended this study by developing a multi-scenario model using probabilistic distributions and stochastic processes to generate energy consumption scenarios based on historical data, thereby accounting for uncertainties in energy demand. Building upon the MILP framework previously developed [19], the new approach introduces a stochastic solution by feeding the model with time-series data derived from a probabilistic representation of seasonal variations. This enhancement improves robustness compared to the earlier deterministic formulation, and helps reduce investment risks associated with the technology [20]. However, the SWAC model used in this study is a linear model that is decoupled from the building, making it highly simplified compared to a real installation. The cooling demand is estimated based on measured electricity consumption from conventional chillers and an average COP (Coefficient of Performance) value, representing another approximation in this study. Additionally, the SWAC model has not been experimentally validated, leaving uncertainty regarding its actual performance under varying operational conditions.

3.2.3. *Coupling configurations*

Design variations and coupling options for SWAC systems are also being explored. In an article, Hunt et al. propose the following adjustments to the conventional system design [21]: (i) increasing the excavation depth of the technical room to 20 m below the sea, instead of the typical 2–5 m, allowing the seawater intake flowrate to double without the risk of cavitation (due to the increased hydrostatic pressure at greater depths). (ii) coupling SWAC with cold seawater thermal energy storage enables the system to handle high variability in cooling demand throughout the day.

The authors estimate that this design doubles the cooling capacity of the installation while requiring only 55 % of the capital investment costs and 83 % of the operational costs compared to installing a completely new system.

In another study, Hunt et al. explores the coupling of SWAC with a cooling distribution network using ammonia instead of a chilled water loop. The vaporization latent heat of ammonia allows for superior heat transfer compared to water while maintaining a 10 °C temperature difference on the distribution side. The proposed secondary network layout consists of four heat exchangers in series, each connected to an ammonia loop at a pressure of 6, 7, or 8 bar, depending on the seawater inlet temperature (5, 8, or 12 °C). The final heat exchanger is coupled with a chilled water network operating at 18/27 °C (with a 16/25 °C temperature range on the seawater side). The design also incorporates a decentralized ammonia storage unit located near the client facility [22]. However, despite the potential increase in cooling capacity offered by these improvements, they significantly increase the capital investment costs of technology, which is already the main barrier to SWAC development worldwide. Exploring alternative designs to reduce the initial cost of the technology is crucial for its global expansion. In regions where deep ocean waters are not directly accessible, similar approaches to SWAC have been developed, utilizing naturally cold water from other sources, such as lakes.

3.3. *Lake Source Cooling (LSC)*

The Lake Source Cooling (LSC) technology can operate on the same fundamental principles as SWAC, either by using cold lake water directly to cool buildings or by utilizing lake water as a heat sink for a heat pump (cooling/heating) or a vapor compression system (cooling only). The only significant difference between shallow SWAC and LSC systems lies in the corrosion issues associated with the use of seawater. The potential of lake-fed cooling networks has been studied in temperate climates, such as in Europe. A study by Eggimann et al. provided an initial assessment of this potential [23]. Cooling networks using lakes are primarily limited by their availability, while the distribution of energy demand influences both energy savings and the balance between operating costs and investments. The study found that the cooling demand of buildings located near lakes (within 1.5 km) significantly exceeds the technical and economical viable supply potential. According to their findings, LSC systems could cover around 17 % of the cooling needs of buildings near European lakes in a technically and economically viable manner. The deployment of these systems could lead to annual electricity savings of 0.4–0.8 TWh in Europe, particularly in Italy, Germany, Switzerland, and Turkey. Additional benefits of integrating these systems could emerge if the potential for reducing peak cooling demand, especially during heat waves, is considered. However, the implementation of lake-based cooling networks remains sensitive to key factors such as electricity prices, interest rates, carbon taxes, and climate change. The integration of all technically and economically viable cooling systems is expected to have a minimal impact on lake temperature, with temperature increases of less than 0.5 °C in most cases.

3.4. *Water-assisted systems: "shallow SWAC"*

Seawater can also be used as a heat sink in a conventional system when the source temperature is not low enough for direct use. Seawater heat pumps (SWHP), also known as *thalassothermal systems* (from Greek Thalassa, meaning sea or ocean – "heat of the sea"), extract water from shallow depths and are beneficial for both heating and cooling needs

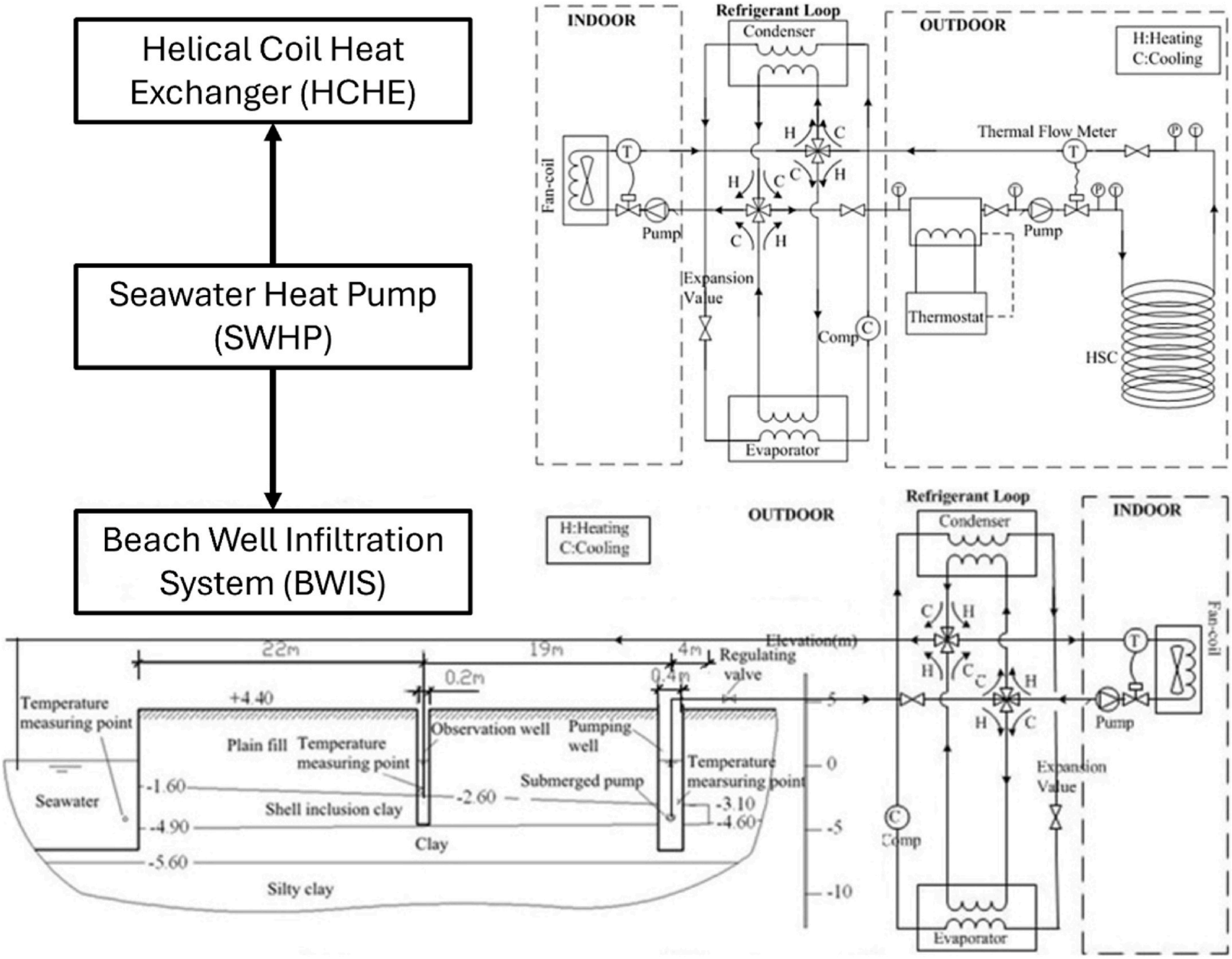

Fig. 4. Schematic of the Sea Water Heat Pump system used for Helical Coil Heat Exchanger and Beach Well Infiltration System [25].

depending on the season: (i) in summer, the heat pump operates like a chilled water system, using seawater to cool the condenser. The seawater is pumped into the heat pump condenser, where heat is transferred from the refrigerant to the seawater. The chilled water, produced in the evaporator, is then distributed to buildings. (ii) in winter, seawater serves as a heat source. Heat is extracted from seawater and transferred to the refrigerant in the evaporator. The hot water, generated in the condenser, is then transported through the distribution network to heat buildings [24]. Zhen et al. assessed the efficiency and cost of SWHP systems compared to air-source heat pumps (ASHP) under extreme winter conditions through experiments conducted in Tianjin Port, northern China. Two seawater heat pump systems, illustrated in Fig. 4 were analyzed.

The first system uses a Helical Coil Heat Exchanger (HCHE) and consists of three loops: (i) the first one uses a mixture of water and ethylene glycol to transfer thermal energy from seawater to the system, (ii) the second one for the refrigerant in the heat pump cycle, (iii) the third one with freshwater to transport thermal energy to the heat exchanger inside the building. The other system uses a Beach Well Infiltration System (BWIS), consisting of three loops. However, it differs in that seawater is directly extracted using a submerged pump in an infiltration well. This eliminates the need for the ethylene glycol loop and the helical coil heat exchanger (HCHE) but requires corrosion protection for the heat pump cycle. The results show that the HCHE system freezes when operating in extremely cold environments, which affects its heat exchange coefficient. As a result, the BWIS system performs better under low-temperature conditions. It is worth mentioning that variations in glycol proportions to prevent freezing issues were not discussed in the article. The study also reveals that the conventional ASHP (Air Source Heat Pump) outperforms the HCHE during winter when seawater temperatures exceed 6 °C. Furthermore, the average COP (Coefficient of Performance) calculated over the study period for heating mode is: (i) 2.44 for the ASHP, (ii) 2.88 for the HCHE, (iii) 3.17 for the BWIS. An economic analysis indicates that the overall lifetime cost of the SWHP system (HCHE or BWIS) is lower than that of the ASHP system. However, the construction of the BWIS is more challenging due to geological constraints and is less cost-effective than the HCHE, despite its higher efficiency [23].

Alternatively, thermal energy from seawater can be harnessed through absorption refrigeration cycles. Hu et al. [26] compared two compression-assisted ammonia-water absorption refrigeration cycles designed to meet the freezing and seafood preservation needs in coastal areas and offshore islands. These two cycle, referred to as “low-pressure” and “high-pressure”, utilize cold seawater at 8 °C and warm seawater at 29 °C to achieve refrigeration temperatures of −15 °C. Both cycles, illustrated in Fig. 5, operate as follows: (i) High-pressure cycle: Warm surface seawater heats the ammonia-rich solution in the generator (point 2), causing ammonia to desorb and form a refrigerant vapor. This vapor is compressed (line 6), increasing its pressure and temperature, then condensed by cold deep seawater in the condenser (line 7), forming a high-pressure liquid (line 8). The liquid expands through valve V1 into the evaporator (line 9), where it absorbs heat and evaporates, producing a cooling effect (line 10). The resulting low-pressure vapor is absorbed by the weak ammonia solution in the absorber, regenerating a rich solution (line 11), which is then pumped back to the generator via a solution heat exchanger (SHEX, line 4). This heat exchanger improves system efficiency by preheating the rich solution using heat recovered from the weak solution exiting the generator (line 5), thus completing the cycle (Fig. 5a). (ii) Low-pressure cycle: Similar to the high-pressure cycle, but here, the compressor compresses low-pressure refrigerant vapor after evaporation rather than intermediate-pressure vapor. Warm and cold seawater still play a role in desorption and heat dissipation during the condensation and absorption processes (Fig. 5b).

The results show that the low-pressure cycle offers better exergetic efficiency, while both cycles outperform conventional vapor compression refrigeration in terms of energy savings. Additionally, the study reveals that lower temperatures for cold seawater or higher temperatures for warm surface seawater further enhance the performance of both cycles. While the low-pressure cycle stands out for its higher energy efficiency, the high-pressure cycle demonstrates a better cost-effectiveness ratio under the studied conditions.

The aforementioned works show that SWAC and other similar systems can achieve promising energy performance in various contexts. However, it is crucial to evaluate them under real-world conditions to better understand their potential and limitations. Existing installations and case studies provide valuable feedback in this regard.

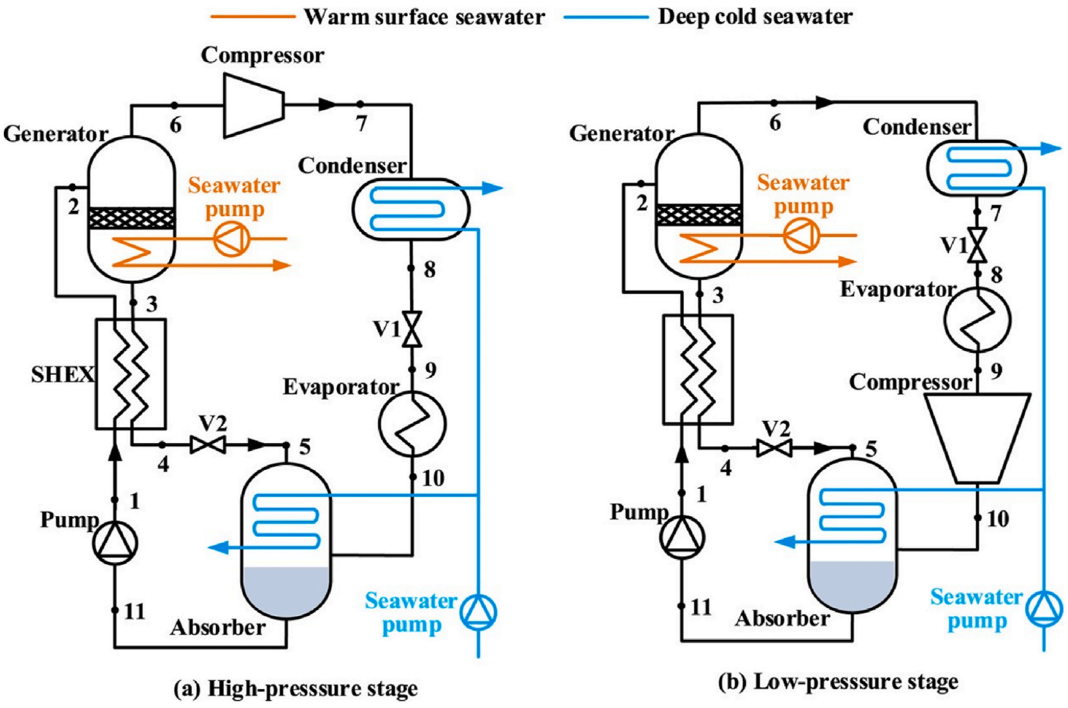

Fig. 5. Schematic of the compression-assisted absorption refrigeration cycles [26].

3.5. *Case studies and successful deployments*

3.5.1. *Existing installations*

According to Hunt et al. [14], SWAC has significant potential in tropical regions, particularly on islands where electricity prices are very high. In locations where the cost of cooling energy exceeds $\$0.04/\ \text{kWh}_t$, SWAC becomes an attractive alternative compared to conventional systems. The most suitable locations for SWAC deployment include islands in the Caribbean, the Pacific, and the Indian Ocean. Sanjivy et al. confirmed the relevance of these areas by mapping the global SWAC potential, providing the pipeline lengths required for a SWAC system at each coastal point. They also showed that the number of suitable areas for SWAC increases when raising the drawing temperature [15]. However, despite this high potential, there are currently only three operational SWAC installations, all of which are located in French Polynesia (Fig. 6).

Tahiti and the other islands of French Polynesia are well-suited for SWAC technology due to their steep oceanic slope, which plunges to over 900 m near the coast. This allows for relatively easy access to deep seawater at approximately 5 °C. The first SWAC system was developed by Pacific Beachcomber SA for the Intercontinental Hotel in Bora Bora in 2006. However, since the installation was not instrumented at the time of implementation, its exact performance remains unknown. In 2013, Pacific Beachcomber SA installed a second SWAC system at The Brando Hotel on the Tetiaroa Atoll (Fig. 7a). This installation was instrumented in 2021, and its operation was studied to assess the performance of SWAC as discussed in the introduction. Finally, the SWAC system at the French Polynesia Hospital Center (CHPF), located in Tahiti, has been operational since July 2022 and includes an integrated instrumentation system (Fig. 7b) [7].

Table 1 summarizes the characteristics of the three SWAC installations in French Polynesia. While the intake depth is similar for all three systems, the intake pipeline lengths vary significantly due to bathymetric differences, ranging from 2300 m in Bora Bora to 3800 m in Tahiti. The diameter of the intake pipelines also varies considerably between the installations, depending on the nominal cooling capacity of each system.

In addition to these SWAC installations, several Lake Source Cooling (LSC) systems are operational in temperate-climate countries, where cooling demands are generally lower. These systems either use cold lake water directly, assist a heat pump, or combine both approaches. Switzerland stands out for its numerous lake-based cooling systems, particularly those utilizing Lake Geneva, as documented in Pierre-Alain Viquerat's thesis [28]. One notable installation is Versoix-Centre, near Geneva, commissioned in 2009, where it pumps water from a depth of 50 m at a nominal flow rate of 600 m^3/h before discharging it into the Versoix River. This system provides both heating, assisted by lake-source heat pumps (6.6 GWh/year), and free cooling for air conditioning (1.8 GWh/year), serving approximately 60,000 m^2 of buildings. Notably, the performance data for most of these installations are not publicly available except for specific cases. The Nestlé global headquarters in Vevey, also located next to Lake Geneva, is equipped with an 8 MWt cooling network serving both offices and data centers. This system was originally installed in 1957 and modernized in 1995. It draws water from a depth of 50 m and discharges it at approximately 9 m. At Lausanne, the École Polytechnique Fédérale de Lausanne (EPFL) campus also operates an LSC system, drawing water from 70 m deep at 6 °C. With a nominal flow rate of 940 m^3/h, the system discharges water into the Sorge River at temperatures ranging from 12 to 14 °C. The network is designed to meet heating needs via heat pumps, while cooling is provided directly through heat exchangers, with a nominal capacity of 4.8 MWt.

Another major installation is GLN-MS (Genève-Lac-Nations and Merck-Serono), located 2 km from downtown Geneva. This system pumps water from a depth of 37 m and supplies 15.7 MWt of cooling and 3 MWt of heating to nearby buildings. The water is then discharged back into the lake at a depth of 4.5 m. The total cost of this system is estimated at €32 million, covering a 6 km pipeline network. Its Energy Efficiency Ratio (EER) is 6.8, but according to a five-year operational review (2005–2010), the efficiency varies significantly [28]. Other Lake Source Cooling (LSC) systems exist worldwide, such as in Toronto, Canada, where an LSC system was integrated into the district cooling network of the city's administrative and university area in 2004. Water is pumped from a depth of 83 m in Lake Ontario, where temperatures remain around 4–5 °C, using three intake pipelines spaced approximately 800 m apart. This system combines material and energy recovery by first using lake water for potable water production. Before being distributed as drinking water, its cooling energy is transferred to a closed-loop chilled water network, which distributes cooling to connected buildings. The total cooling capacity of this network is 363 MWt, with 60 MWt directly sourced from the lake, the rest being produced by vapor compression

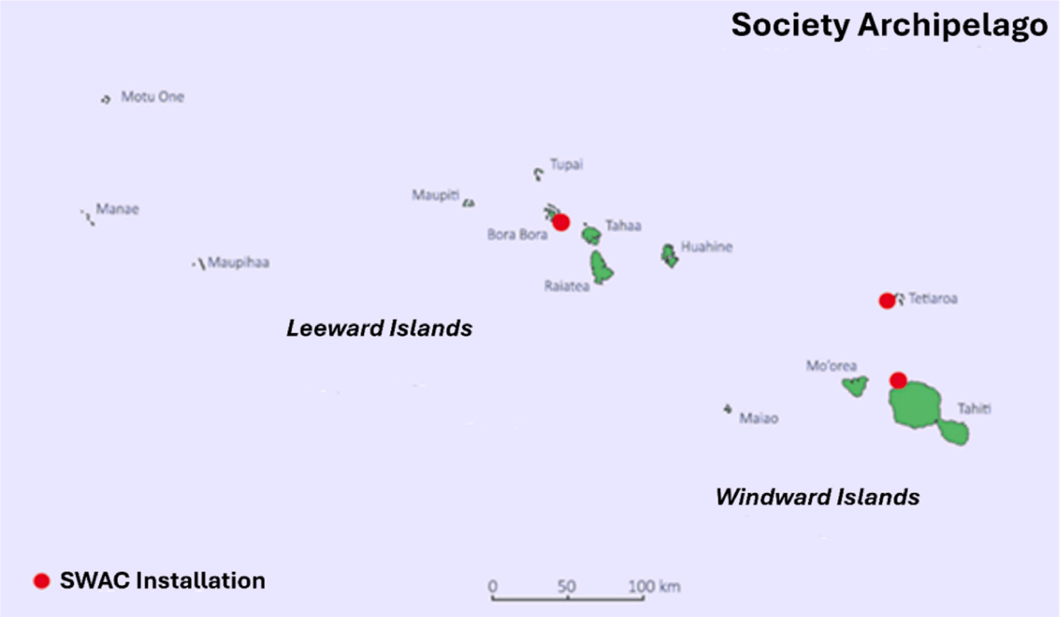

Fig. 6. Map of operational SWAC installations (base map adapted from Ref. [27]).

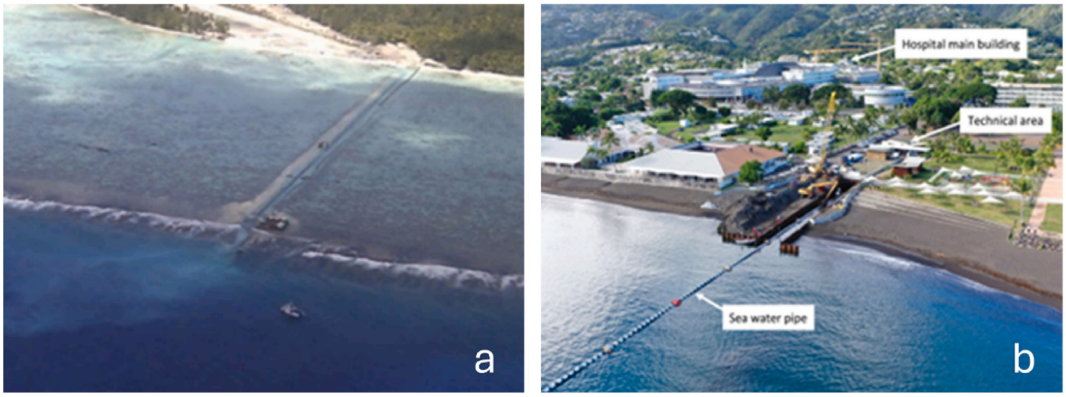

Fig. 7. Aerial view of the sea water loop of The Brando (a) and the French Polynesia Hospital Center (b) [16].

Table 1
Characteristics of SWAC installations in French Polynesia [8,16].

Location	Year	Building type	Drawing depth	Drawing pipeline length	Drawing pipeline diameter	Cooling power	Investment cost	SCOP
Bora Bora	2006	Hotel	−915 m	2300 m	400 mm	1.6 MW	5,5 M€	Unknown
Tetiaroa	2013	Hotel	−960 m	2618 m	368/383 mm	2.4 MW	10 M€	25.6
Tahiti	2022	Hospital	−900 m	3800 m	710 mm	6 MW	30 M€	26.6

cycles. This network air-conditions approximately 100 skyscrapers, covering 3.2 million square meters of office space, and saves an estimated 1.7 GWh of electricity per year [28–30].

A similar system was implemented at Cornell University, USA, in 2000, using water from Lake Cayuga pumped from 76 m deep. This system provides 71 MWt of cooling capacity, servicing 75 buildings over a total area of 1.2 million square meters. Before its implementation, the university relied on a chilled water network powered by six refrigeration units, but new regulations, aging infrastructure, increasing cooling demand (106 GWh/year between 2000 and 2003), and rising electricity costs led to the adoption of the LSC system [28,31,32].

Regarding sea water heat pump (SWHP), there are numerous systems in operation globally, where conventional air conditioning systems use seawater as a heat sink. One of the most notable examples is the Sydney Opera House, which uses seawater from Sydney Harbour to power a heat pump system [33]. Similarly, in France, the “Fraîcheur de Paris” district cooling network (formerly “Climespace”) utilizes water from the Seine River for conventional cooling production, integrating ice storage and chilled water storage systems. This network claims a COP of 4, although details on its calculation method are not specified [34,35]. More recently, the “Thassalia” marine geothermal plant, inaugurated in 2016 at the Grand Port Maritime of Marseille (France), extracts surface seawater to supply a heat pump-driven distribution network, providing both heating (10.8 MWt) and cooling (13.6 MWt) to connected buildings [36–38].

3.5.2. *Feasibility studies*

Beyond functional SWAC systems, various case studies have been conducted, either as feasibility studies by companies like Makai Ocean Engineering or through research presented in scientific literature. These studies mainly concern the Caribbean region, with the SWAC projects of Montego Bay and Puerto Plata, and French Polynesia with the SWAC of Papeete.

The Montego Bay SWAC project studied by Makai Ocean Engineering [39] requires an initial investment of $100M to provide a nominal cooling capacity of 27 MWt. The Levelized Cost of Energy (LCOE) is evaluated at $983.2/kW/year, representing a 34 % reduction compared to the cost of conventional air conditioning, estimated at $1492/kW/year. From a technical perspective, the Montego Bay SWAC is designed with an intake pipeline with an outer diameter of 1200 mm (inner diameters not specified), extending 4.5 km in length and reaching a depth of 879 m. The discharge pipeline has an outer diameter of 1000 mm, a length of 1.1 km, and a depth of 50 m. The system’s primary pumps have a nominal mass flow rate of 1207 kg/s, with an electrical power of 267 kWe. The seawater is extracted at a temperature of 6.2 °C, allowing the chilled water temperature (from the secondary loop) to reach 7.2 °C before being distributed through a 41.2 km distribution network. The temperature difference between the chilled water and the seawater source seems too small to be realistic when compared to actual installations, considering potential heat losses along the intake pipeline and the heat exchanger pinch (minimum temperature difference between the hot and cold fluids). The study does not provide details on these aspects; it only mentions that the chilled water loop is well insulated. The operating cost (OPEX) is estimated at $324.1/kW/year, with an additional periodic cost, not detailed by the authors, of $23/kW/year. The study concludes that the Montego Bay SWAC remains economically viable compared to a conventional solution, even at 50 % of its nominal capacity.

The other SWAC project, located in Puerto Plata and also evaluated by Makai, requires an initial investment of $68M to provide a nominal cooling capacity of 24 MW. The LCOE for this system is even more advantageous, amounting to $692.4/kW/year, representing a 48 % reduction compared to the LCOE of $1334/kW/year for a conventional air conditioning system. The technical specifications of the Puerto Plata SWAC include an intake pipeline with an outer diameter of 1100 mm, extending 8 km in length and reaching a depth of 1082 m. The discharge pipeline is smaller, with an outer diameter of 800 mm, a length of 2.2 km, and a depth of 50 m. The primary pumps provide a nominal mass flow rate of 761 kg/s with an electrical power consumption of 200 kWe. The seawater is extracted at a temperature of 5.8 °C at the heat exchanger inlet, cooling the chilled water to 7.2 °C, as in Montego Bay, before being distributed through a secondary loop of 13.4 km. The operating cost for this project is estimated at $212.7/kW/year, with an additional periodic cost, not detailed by the authors, of $17/kW/year. Unlike the Montego Bay project, this system could benefit from coupling with a sensible heat storage system with an estimated volume of 11000 m^3, but it does not require supplementary cooling from conventional chilled water production units. It is worth noting that, although the economic assessment in the study is based on a levelized lifetime cost analysis, the exact duration of the assumed project lifetime is not disclosed. This lack of explicit lifetime specification may limit the transparency and comparability of the reported cost figures [39].

In French Polynesia, the feasibility study for a SWAC system in the urban area of Papeete, conducted by Airaro and Luseo, explores two distinct solutions. The first solution, without a storage system, could be technically viable, but its financial model is unfavorable, with an internal rate of return (IRR) of −9.6 %, which would require increasing cooling demand in the area through various regulatory measures, in order to make the project economically viable. The project requires an investment of $71 million to provide a cooling capacity of 11 MWt.

The technical specifications include: (i) an intake pipeline with an outer diameter of 1000 mm, extending 4.36 km and reaching a depth of 986 m, (ii) a discharge pipeline with an outer diameter of 1000 mm, extending 1.4 km and reaching a depth of 60 m, (iii) primary pumps with a nominal mass flow rate of 509 kg/s and an electrical power of 89 kWe, (iv) secondary pumps with a flow rate of 519 kg/s and an electrical power of 235 kWe at nominal operation, (v) seawater is extracted at a temperature of 4.6 °C at the intake point, cooling the chilled water to 7 °C before being distributed through a network covering three municipalities: Papeete (4.3 km), Paofai (0.6 km), and Faa'a (4.5 km) [40].

The second solution proposed for the Papeete urban area includes a storage system. Although financially more favorable, it still has a negative IRR of −7 %. The investment is spread over several years, with a total cost of $65 million to provide a final cooling capacity of 5 MW. The technical specifications include: (i) an intake and discharge pipeline, both with an outer diameter of 710 mm. (ii) primary pumps with a flow rate of 231 kg/s and an electrical power of 50 kWe. (iii) a storage system consisting of a 5455 m^3 tank for sensible heat storage or two tanks of 63 m^3 and 135 m^3 for latent heat storage in the form of ice, requiring an auxiliary chiller [40].

The key characteristics of the SWAC installations studied in these feasibility studies are summarized in the following table (Table 2).

The reported LCOE values for the SWAC systems in Montego Bay and Puerto Plata range from 692 to 983 $/kW/year, corresponding to a 34 %–48 % reduction compared to conventional cooling solutions. This difference is largely attributed to the size of the secondary distribution loop, which significantly impacts both CAPEX and OPEX. A longer loop increases installation costs due to greater pipeline length and complexity, while also raising operating costs through higher energy consumption from secondary pumping. These findings highlight the importance of optimizing network design to improve the economic performance of SWAC systems.

Table 2
Summary table of the technical and economic characteristics of SWAC projects (not built; based on feasibility studies) in the Caribbean and French Polynesia [39,40].

Characteristics	SWAC of Montego Bay (Caribbean)	SWAC of Puerto Plata (Caribbean)	SWAC of Papeete without storage (French Polynesia)	SWAC of Papeete with storage (French Polynesia)
Nominal cooling capacity	27 MW	24 MW	11 MW	5 MW
Initial Investment (CAPEX)	100 M$	68 M$	71 M$	65 M$
Operating cost (OPEX)	324,1 $/kW/year	212,7 $/kW/year	Not specified	Not specified
Levelized Cost of Energy (LCOE)	983,2 $/kW/year	692,4 $/kW/year	Not specified	Not specified
Outer diameter of intake pipeline	1200 mm	1100 mm	1000 mm	710 mm
Length of intake pipeline	4.5 km	8 km	4.36 km	4.4 km
Intake depth	879 m	1082 m	986 m	999 m
Outer diameter of discharge pipeline	1000 mm	800 mm	1000 mm	710 mm
Length of discharge pipeline	1.1 km	2.2 km	1.4 km	1.4 km
Discharge depth	50 m	50 m	60 m	60 m
Primary flow rate	1207 kg/s	761 kg/s	509 kg/s	231 kg/s
Primary electrical power	267 kW	199 kW	89 kW	50 kW
Secondary flow rate	1149 kg/s	724 kg/s	519 kg/s	Year 1 : 232 kg/s Year 10 : 519 kg/s
Secondary electrical power	995 kW	350 kW	235 kW	235 kW
Seawater intake temperature	6.2 °C	5.8 °C	4.6 °C	4.5 °C
Chilled water supply temperature	7.2 °C	7.2 °C	7 °C	7 °C
Distribution network length	41.2 km	13.4 km	Papeete: 4.3 km Paofai: 0.6 km Faaa: 4.5 km	Papeete: 4.3 km Paofai: 0.6 km Faaa: 4.5 km
Storage system	None	Sensible: 11000 m^3	None	Sensible: 5455 m^3/ Latent: 63 m^3 and 135 m^3

3.5.3. *Design studies*

In addition to the feasibility studies conducted for SWAC projects in the Caribbean and French Polynesia, summarized in Table 2, two design studies are also worth mentioning. One is a technical feasibility study for a SWAC system in Tuvalu, while the other explores financing methods for the implementation of a SWAC project at the U.S. Naval Base in Guam.

The first study in Tuvalu focuses on the design of a SWAC system for the campus of the University of the South Pacific. This study assessed the campus's air conditioning needs, estimated at 117 kW, using CAMEL software [41]. A 1/10 scale model of the campus was built in the university's mechanical engineering workshop. This model, equipped with electric heaters to simulate internal and external thermal loads, was used to test cooling efficiency with chilled water at 7 °C.

The tests demonstrated that the system could cool the air to 22 °C, confirming the technical feasibility of SWAC for the campus. Additionally, an economic analysis compared the SWAC system to conventional air conditioning systems, such as split systems and mechanical vapor compression (MVC) systems equipped with chilled water units. The analysis revealed that the SWAC system would have a return on investment (ROI) between 8.6 and 12.6 years. Furthermore, the study showed that this project would reduce carbon dioxide emissions by 2.5 tons per month, highlighting the environmental benefits of SWAC [42].

The second study examines financing options for a SWAC project at the U.S. Naval Base in Guam. Various strategies were analyzed, and the study concluded that an Energy Performance Contract (EPC) is the most suitable solution. Despite the high initial costs of the design and construction of such a system, this type of contract allows the project to proceed without upfront investment, using energy savings to cover expenses while also transferring most of the risks to the service provider [43].

Several research studies have emerged from the feasibility studies conducted for the two SWAC projects in the Caribbean. One study explored the impact of incentive policies on SWAC adoption, revealing that regional cooperation among multiple countries could be more effective than individual national approaches in promoting this technology. A system dynamics model, designed as a policy decision-making tool, was used to simulate different adoption scenarios, incorporating a multi-dimensional scaling analysis to identify interactions and influences between countries. This model provides a visualization of how policies and regional cooperation can accelerate SWAC adoption. The modeling results suggest that a regional approach could increase SWAC adoption to 60 % by 2030, compared to 36 % with isolated national policies [44]. In another study, the potential for deep ocean water (DOW) extraction, considering environmental, technological, and socio-economic constraints, was analyzed to provide a realistic estimate of the amount of seawater that could be extracted for five Caribbean cities: Montego Bay (Jamaica), Puerto Plata (Dominican Republic), San Andres (Colombia), Bridgetown (Barbados), and Willemstad (Curaçao). The methodology relied on a steady-state numerical model that considered temperature, salinity, and ocean currents to evaluate the potential for seawater extraction for SWAC and OTEC systems.

The results indicate that the average extraction potential is around 51250 kg/s per city, which is sufficient to cover over 100 % of annual air conditioning needs (via SWAC) and 60 % of electricity demand (via OTEC) in these locations. However, this potential fluctuates seasonally, with peak extraction between December and March and lower availability between August and October [45]. SWAC technology is also attracting increasing interest in other regions, including Mayotte, Oman, Florida, Egypt, Mauritius, and Réunion Island, as shown in Table 3. Finally, in France, The SWACool project evaluated the cooling demand of multiple buildings to optimize their energy efficiency, with two of them now connected to the Thassalia network (Marseille, France) mentioned in Section 3.5.1 [46].

In addition to SWAC systems, Lake Source Cooling (LSC) systems and Seawater Heat Pumps (SWHP) have also been the subject of theoretical studies, aiming to demonstrate their potential in various contexts.

The first example is a comparison between an LSC system and a conventional vapor compression system for an underground mine in Canada. This system utilizes cold lake water from a lake located 3.42 km away, where water is drawn from 50 m deep at a temperature of 5 °C. The study revealed that this system could provide 21.8 MW of cooling capacity, with a 23 % reduction in initial investment costs compared to a conventional system, representing $8.7 million in savings. This is primarily due to the absence of heavy and expensive mechanical refrigeration equipment, which is typically required for cooling deep underground mines. These systems require significant investments, as heat from self-compression and mining equipment necessitates the installation of large-scale cooling systems. This system would maintain a temperature of 25 °C in the mine, meeting safety requirements for underground work environments while being economically more viable [53].

Another example concerns a seawater heat pump (SWHP) system proposed for an urban development project in Dalian, China. This SWHP system would be capable of providing 68 MW of heating in winter and 76 MW of cooling in summer. The results of this feasibility study show that, although the initial investment for the SWHP system is higher than that of a conventional system (respectively $47.7 million and $33.5 million), the annual operating costs are significantly lower for the SWHP solution. The system enables long-term savings, with a return on investment estimated at approximately eight years. Furthermore, the SWHP system offers substantial environmental benefits, reducing annual coal consumption by nearly 13,000 tons, as well as CO_2, SO_2, NO_x, and other pollutant emissions. Environmental simulations also show that the impact of seawater discharge on the marine ecosystem is negligible [24].

Finally, a recent study conducted in South Korea evaluated the feasibility of a hybrid urban cooling system using seawater between 5.5 °C and 11.5 °C, specifically adapted to intake conditions experiencing large temperature variations throughout the year. This hybrid model combines direct cooling via a heat exchanger, a centrifugal compression chiller assisted by seawater, and an absorption chiller powered by a district heating network. The results show that, even with variations in seawater temperature, the system remains competitive, achieving primary energy savings of approximately 50 %. Under constant temperature conditions, it could offer up to an additional 30 % in savings, further enhancing its competitiveness [54].

Table 3
Interest in SWAC in different locations.

Location	Interest
Mayotte	SWAC is being studied as part of energy transition scenarios (2011) [47].
Oman	SWAC could be advantageously coupled with desalination systems and marine permaculture (2017) [48].
Florida	The availability of cold seawater resources could reduce air conditioning energy consumption by 50 % and 54 % in Fort Lauderdale and Miami, respectively, according to a simplified model of a 3.5 MWt SWAC system (2012–2013) [49,50].
Egypt	SWAC is being considered for a hotel complex (2009) [51].
Mauritius	SWAC could significantly reduce energy consumption for a data center (2012) [52].

4. Ocean Thermal Energy Conversion (OTEC)

4.1. Operating principle

The OTEC (Ocean Thermal Energy Conversion) technology uses the temperature difference between deep seawater and the ocean surface to drive a heat engine coupled to a generator, thereby producing electricity. This temperature difference is greatest in equatorial and tropical waters, where the gap is approximately 20 °C, with deep seawater between 4 and 6 °C and surface water between 25 and 30 °C. The conversion of thermal energy into electrical energy is achieved through a thermodynamic cycle, which can be open, closed, or hybrid. The three types of cycles applicable to OTEC are illustrated in Fig. 8 below.

The closed Rankine cycle is the most studied (Fig. 8a), as it is more efficient than its open or hybrid counterparts [56]. The main components of a closed cycle SWAC plant are described in Table 4.

Regarding the open cycle, it directly uses warm seawater as the working fluid. The warm seawater is evaporated in a vacuum chamber (flash evaporator), producing water vapor. This vapor drives the turbine, generating mechanical work, before being condensed by cold seawater. An advantage of the open cycle is its ability to produce freshwater from the condensate of the vapor. However, this cycle is more challenging to implement due to the low pressures at the turbine inlet and outlet, which require large turbines. Moreover, maintaining the low-pressure necessitates a vacuum pump, whose energy consumption is non-negligible, unlike the water pump used in the closed-cycle system, which has a much smaller impact on overall efficiency.

The hybrid cycle combines features of both the closed and open cycles. In this cycle, warm seawater is first evaporated in a vacuum chamber, as in the open cycle. However, instead of using the vapor directly in a turbine, it is sent to an evaporator of an ORC (closed cycle), where it transfers its heat to a working fluid. This allows for more efficient heat recovery and improves energy efficiency. Like the open cycle, the hybrid cycle also produces freshwater but shares the same drawbacks, notably the use of a vacuum pump, which reduces overall efficiency.

The maximum efficiency of this type of cycle, known as Carnot efficiency, is 6.7 % for cold and hot sources at 5 °C and 25 °C, respectively. This low efficiency is due to the relatively small temperature difference between the hot and cold sources. In practice, the actual efficiency is significantly lower, often between 1 % and 3 %. This is mainly due to irreversibilities in the thermodynamic cycle, pumping power requirements for both warm and cold seawater, and thermal losses in the heat exchangers, which operate with small temperature differences and large surface areas. Moreover, maintaining vacuum conditions in open

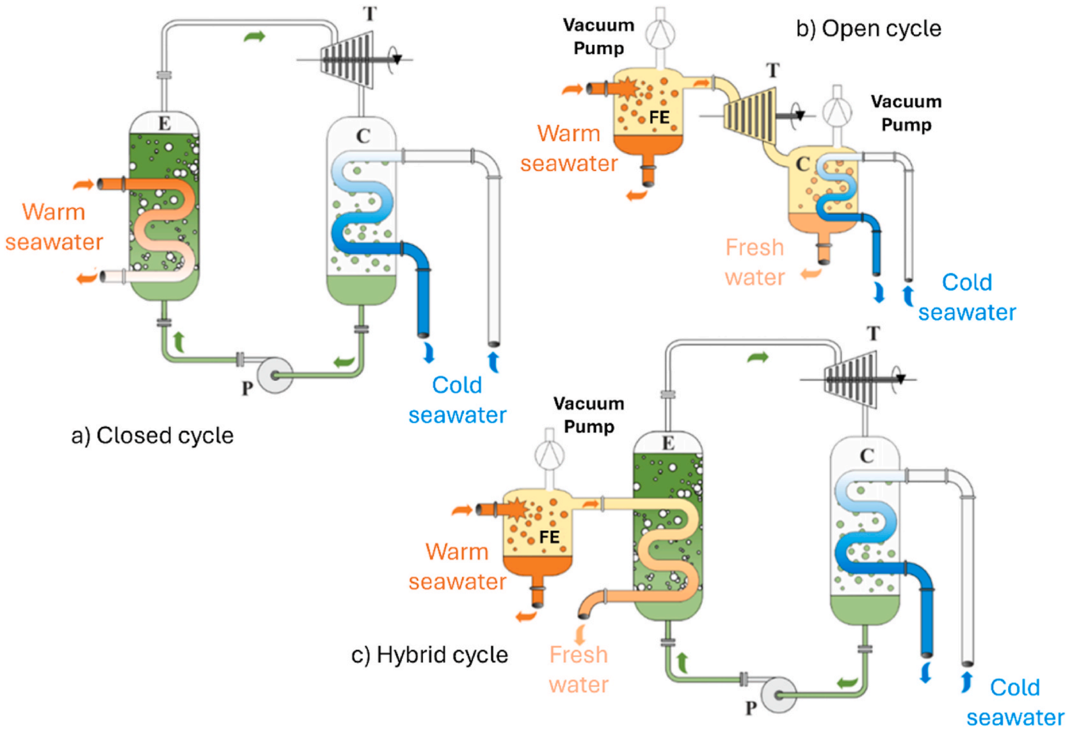

Fig. 8. Basic diagram of a closed (a), open (b), and hybrid cycle (c) of an OTEC installation (FE: Flash Evaporator) [55].

Table 4

Main components of a closed cycle SWAC plant.

Component	Description
Evaporator	A heat exchanger where the working fluid evaporates due to the heat provided by warm seawater.
Turbine	A device in which mechanical work is generated by the flow of working fluid vapor, which is then converted into electricity by an alternator coupled to the turbine.
Condenser	A heat exchanger where the working fluid condenses by releasing its heat to cold seawater.
Working fluid pump	Ensures the circulation of the working fluid by pumping it from the low-pressure side (after condensation) to the high-pressure side (before evaporation).
Seawater pumps	It enables the circulation of cold and warm seawater through their respective heat exchangers (evaporator and condenser).

or hybrid cycles also adds energy loss.

4.2. Existing installations

There are two operational OTEC installations connected to the electrical grid worldwide (Fig. 9). The first installation, developed by Makai Ocean Engineering, is a 105 kWe facility located at NELHA (Natural Energy Laboratory of Hawaii Authority) in Hawaii. This system operates with a closed Rankine cycle and uses ammonia as the working fluid. The structure was built in 2011, and the OTEC system was commissioned in 2015. The primary objective of this installation is the evaluation of heat exchange performance. Connected to the local power grid, this installation is the largest grid-connected OTEC facility [57].

The second system is the OTEC Demonstration Facility located in Kumejima, Okinawa, Japan. This 100 kWe facility, split into two 50 kWe units, operates with a two-stage Rankine cycle, with one unit using R134a as the working fluid and the other using ammonia. Completed in March 2013, this installation, like the Hawaii facility, is primarily designed to simulate and evaluate heat exchanger performance. The system operates continuously in an automated manner and is connected to the local power grid. Since commissioning, data has been collected under various operating conditions. Additionally, the heat exchangers are sized to allow for scalability to larger installations, and the discharged water from the OTEC system is reused in various industries [57, 58].

In addition to the operational OTEC installations in Hawaii and Okinawa, another notable pilot installation is located in South Korea, which was publicly demonstrated at the end of 2013 [60]. Developed by the Korea Research Institute of Ships and Ocean Engineering (KRISO), this OTEC installation has a capacity of 20 kWe and operates with a closed cycle using R32 (Difluoromethane) as the working fluid. Located in Goseong, the facility aims to evaluate system performance under real-world conditions (Fig. 10). An article by Lee et al. presents the design specifications and performance characteristics of this pilot installation [61].

The system operates with a warm seawater temperature of 26.2 °C at a flow rate of 87 kg/s and a cold seawater temperature of 4.9 °C at a flow rate of 44.9 kg/s. The thermal power exchanged at the evaporator and condenser is 1050 kW and 1040 kW, respectively, with a working fluid flow rate of 3.6 kg/s. However, while the actual performance aligns with simulation estimates, in practice, it varies significantly based on the temperature difference between warm and cold seawater: (i) at a temperature difference of 21.3 °C, the system produces an electric power output of 20.1 kWe, with a cycle efficiency of 1.91 % (nominal conditions). (ii) when the temperature difference decreases to 19 °C, the power output drops to 15.5 kWe, with a cycle efficiency of 1.73 %, representing a 21 % reduction. (iii) a further decrease to 17.2 °C results in a 39 % reduction, with a power output of only 12.3 kW and a cycle efficiency of 1.45 %. These results underscore how variations in the temperature of the heat source and sink directly impact system efficiency.

In addition to shore-based and nearshore systems, floating OTEC platforms have been proposed to overcome geographic limitations in areas where steep bathymetry or coastal congestion prevent land-based deployment. These systems, anchored in deep equatorial waters, can access optimal thermal gradients while avoiding coastal constraints. Although still at the prototype stage, floating OTEC presents a promising solution for remote tropical zones and small island states with limited

Fig. 9. Operating OTEC installations in Hawaii (left) and Okinawa (right) [59].

Fig. 10. Pilot OTEC installation in Goseong, South Korea [61].

land availability. Key challenges include offshore maintenance, the submarine power transmission, and higher capital costs, but the KRISO 1 MW Barge Test in September 2019 has demonstrated technical feasibility [57].

5. Socio-environmental considerations

5.1. Environmental impacts

Although deep seawater energy systems represent a promising solution to meet the energy needs of islands and coastal cities, these systems have potential interactions with the marine environment. Environmental impacts may occur both during the construction phase and during operation.

During the construction phase, the installation of intake and discharge pipelines required for onshore SWAC and OTEC systems has an environmental impact that can be minimized through microtunneling and horizontal directional drilling techniques. Offshore OTEC platforms, on the other hand, may disrupt benthic (near the seafloor) and pelagic (far from the seafloor) ecosystems during the installation and construction of pipelines and anchoring systems [62].

During the operational phase, several types of environmental impacts may occur. For example, deep seawater intake and its discharge at a shallower depth can lead to thermal impacts by locally altering surface water temperatures, as well as biological impacts by affecting marine ecosystems, particularly phytoplankton. The potential impact of deep seawater discharge into surface waters for an OTEC plant, also known as artificial upwelling, has been studied in Martinique in the framework of Mélanie Giraud's thesis, specifically focusing on its effects on phytoplankton [63,64]. The impacts were assessed through numerical modeling and in situ microcosm experiments after characterizing the physico-chemical, biogeochemical, and biological properties of the study site: (i) Numerical simulations assessed the thermal impacts for different deep water discharge scenarios. The results indicate that thermal changes should be very minimal and limited to a small area (less than 3 km^2) for a discharge between 45 m and 500 m depth, even for very high flow rates. More precisely, the study quantified the affected surface area (top 150 m) by analyzing two spatial domains: a near-OTEC domain within 10 km of the discharge point and a larger domain extending up to 124 km. For a discharge at 45 m depth, only 1 ± 2 % of the near-OTEC domain and 1 ± 2 % of the large domain showed temperature reductions equal to or greater than -0.3 °C. The impact was calculated on an annual average using numerical simulations, but for the month of June, it was also assessed through an experimental method, which showed no measurable thermal impact (0 %) in either the near-OTEC or the large domain.(ii) Microcosm experiments revealed that the discharge significantly impacts the phytoplankton community only at the maximum chlorophyll when there is a high deep-water input (10 %). A mixture of 2 % deep water with surface water or a discharge at the base of the photic zone should not affect phytoplankton. Therefore, it is recommended to discharge seawater below the base of the euphotic layer (the upper ocean layer where light is intense enough to support photosynthesis) to minimize the risk of disturbances [64,65].

In addition to these two impacts, other additional effects have been identified, although they have not been quantified or studied in depth. These include the following: (i) The intake pipeline could draw in marine organisms, particularly the smallest and least mobile ones, leading to mortality risks due to rapid environmental changes within the system [52,62]. (ii) The solubility of dissolved gases in the pumped seawater is altered by temperature and pressure variations, which can cause the release of dissolved CO_2. However, the amount of CO_2 released remains significantly lower than the emissions from a fossil fuel power plant. Changes in CO_2 concentration affect the pH level of seawater, which may increase concerns about ocean acidification and disrupt the marine ecosystem, biodiversity, and the food chain [66,67]. (iii) These systems can also generate acoustic noise, which may disrupt the communication and behavior of fish and marine mammals [62,68]. (iv) Additionally, the electromagnetic fields from the power transmission cables of offshore systems may affect marine organisms that rely on electroreception for navigation and foraging [62].

In addition to the impacts associated with the normal operation of these systems, accidental impacts may also occur, potentially leading to severe environmental consequences. In the case of closed-cycle OTEC systems, toxic working fluids, such as ammonia, are often used. Potential leaks of these fluids must be strictly monitored to prevent significant environmental damage [69]. Moreover, the chemicals used to control biofouling and corrosion can accumulate in the tissues of marine organisms and spread through the food chain [62,70].

Among the reviewed case studies, very few include quantified environmental assessments. When available, the findings suggest minimal thermal and ecological impact. However, standardization of environmental impact methodologies remains lacking, making comparisons across projects difficult.

5.2. *Social aspects*

Marine energy projects, including those utilizing deep seawater, present significant environmental and technical implications. However, it is equally crucial to consider the social aspects that accompany these projects. The socio-economic dimension plays a key role in the acceptance and success of such initiatives [71].

The social and economic focus in the literature is primarily centered on cost-benefit studies. However, most published works do not sufficiently address the economic needs of local populations or their perspectives on potential environmental changes. Therefore, conducting in-depth local studies is essential to assess the social and economic benefits that deep seawater energy systems can bring to communities. Integrating these communities into the decision-making process helps prevent future challenges that could compromise the viability of these projects.

Despite the lack of studies on the social aspects of these projects, public opinion on SWAC has been examined in Hawaii by Lilley et al. [72]. A postal survey was conducted among residents of Oahu to assess their awareness and opinion of this technology. The survey was sent to 2000 residents across six stratified regions, ensuring a geographically representative sample of the island. The results show that 55 % of respondents were aware of SWAC before the survey, and 62 % supported the installation of a SWAC system in Waikiki, while only 7 % opposed it.

The arguments in favor of SWAC mainly relate to cost savings, the development of innovative technology, better utilization of renewable resources, and the reduction of fossil fuel use. Opponents primarily express environmental concerns related to potential damage to coral reefs and algal proliferation. The main concerns of undecided respondents are more focused on the cost of developing SWAC and its potential impact on local residents, particularly the fear that the high cost of the project may lead to increased economic burdens for the population.

Despite a majority in favor of SWAC, it ranked second to last among nine energy production technologies in terms of priority for development in Hawaii, with photovoltaic solar, wind, and solar thermal energy leading the list. This low ranking is explained by the lack of awareness of SWAC compared to other systems, as well as the fact that SWAC is more suited for large structures than for individual residences.

The study also examined the effects of information on the benefits and potential impacts of SWAC on public support. On the one hand, information about its benefits tends to increase support among undecided individuals but has little effect on opponents. On the other hand, potential negative impacts, such as damage to coral reefs, significantly reduce support even among current proponents.

Multivariate analysis revealed that the most decisive factors in supporting SWAC are the age of participants, their political affiliation, their location, their knowledge of the technology, and the perceived importance of SWAC for tourism, particularly in terms of reducing energy costs for hotels and enhancing the environmental image of tourist destinations. People with higher incomes are less likely to support SWAC, whereas those who believe SWAC will benefit tourism are more inclined to support it. Finally, residents of Waikiki are generally more in favor of SWAC than those from other regions of the island.

The adoption dynamics of innovative technologies like SWAC largely depend on public perceptions and incentive policies. A simulation of SWAC adoption in Jamaica also showed that public support is often limited by the high cost of initial installations and a lack of awareness of the technology's long-term benefits. Governments can play a crucial role by funding the first installations or through financial incentives, such as a policy where the government finances 100 % of the first SWAC pipeline to accelerate the adoption of technology. Increased awareness and information campaigns on the benefits of technology are also beneficial for the acceptance and adoption of SWAC, as seen in the case of Hawaii [73].

Hernández-Romero et al. [74] present a decision-making framework for SWAC system design in tourism complexes that accounts for the influence of a dominant actor—typically the main investor. Their multi-objective model balances stakeholder interests while emphasizing the dominant actor's priorities, often favoring economic goals. Using simulations for hotels in Cancún, the study highlights how incorporating actor dominance affects design outcomes and proposes a flexible approach to better integrate environmental and social considerations.

6. Integrated multi-use systems

6.1. *Desalination*

Commercially available desalination methods are divided into two main categories: thermal technologies and membrane technologies. Although thermal methods have historically been dominant, they are gradually being replaced by membrane technologies, which are less energy intensive. Reverse osmosis (RO) is the most widely used method, accounting for approximately 70 % of the world's desalination installed capacity [75]. The development of deep seawater-based energy systems is also of interest for freshwater production, either through an open-cycle OTEC installation [76], which inherently produces freshwater (see Fig. 8) or by coupling SWAC with a reverse osmosis system rather than operating them as separate systems. In such a configuration, the RO membrane is positioned upstream of the SWAC heat exchanger on the primary seawater loop, allowing simultaneous freshwater and cooling production from the same intake [77].

A modeling study of an open-cycle OTEC system in Mexico [11], highlights its strong potential for co-producing electricity and freshwater. The system can be flexibly adjusted, via seawater flow and equipment sizing, to prioritize either output based on demand. However, increasing electricity production reduces freshwater output, and vice versa. The most cost-effective option supplements existing energy and water networks, while full self-sufficiency, though more environmentally friendly, is significantly more expensive. Most emissions stem from seawater pumping, yet the system can cut greenhouse gas emissions by up to 95 % compared to conventional solutions.

Hybrid systems combining ORC and desalination have also been proposed to produce both electricity and freshwater simultaneously. Modeling results from Ma et al. indicate that a 100 kW OTEC cycle of this type could also produce 58.874 tons of freshwater per day [78].

Continuing in the pursuit of maximizing the utilization of deep seawater, a study [79] focused on developing a new cycle that combines cooling, desalination, and electricity generation. This cycle integrates a Kalina cycle using an ammonia-water mixture as the working fluid, an ejector refrigeration cycle (ERC), and a spray flash evaporation (SFE) desalination unit. The system was modeled in steady-state conditions, and a sensitivity analysis was conducted on operational parameters such as pressure, steam generation temperature, ammonia concentration, and condensation pressure to assess the thermodynamic and exergoeconomic performance of the system. The results indicate that the proposed cycle outperforms both the standalone Kalina cycle and multi-generation systems based on the ORC cycle in terms of energy efficiency, exergy efficiency, and net electricity production [79].

Other theoretical studies have also been conducted, such as one in Malé, Maldives, on a SWAC and desalination coupling that allows for the simultaneous production of 49 MWt of cooling power and 86400 tons of freshwater per day, with an electricity consumption of 12 MWe supplied by the power grid. This configuration results in seawater discharge temperatures between 15 and 18 °C above intake temperature, compared to 5–7 °C for a conventional SWAC system, thereby better utilizing the thermal potential of deep seawater [77].

6.2. Aquaculture

Food security is also becoming a major issue as the global population continues to grow and agricultural land degrades. The use of deep seawater to fertilize the oceans, potentially increasing marine production, could become increasingly relevant. Despite the potential environmental impacts associated with the discharge of deep seawater at the surface, as described in Section 5.1, this discharge can also be repurposed for aquaculture due to its lower temperature compared to surface waters and its richness in nutrients, which are characteristic of seawater located below the euphotic zone of the oceans. Multiple experiments conducted in Toyama Bay and off the coast of Ikituki Island in Japan have demonstrated that an increase in nutrients in seawater can stimulate primary production, particularly the growth of phytoplankton, which in turn enhances secondary production, such as that of plankton-eating fish like sardines or anchovies [80].

The use of deep seawater for aquaculture applications is being considered in Taiwan [81], particularly in the eastern part of the country. Since the initial cost of deep seawater pumping is a deterrent, two solutions have been proposed. The first involves repurposing the discharge from an OTEC plant by using this water for aquaculture applications before releasing it. The second focuses exclusively on salmon aquaculture, pumping water from a depth of approximately 250–300 m at a temperature between 12 and 15 °C. This water would be maximized through reuse at different production stages before being discharged back into the ocean. In this way, the effluent produced by salmon aquaculture can first be used for the cultivation of crustaceans or algae, then reused in a second phase for fish farming [82].

Ultimately, it seems crucial to propose an integrated solution that addresses electricity, cooling, potable water, and food production needs to develop deep seawater-based energy systems. This approach illustrated in Fig. 11, which combines OTEC, SWAC, desalination systems, and aquaculture, offers synergies that enhance the overall profitability of the system.

This integrated model illustrates the principles of sustainable system design through resource efficiency, energy recovery, and co-product generation. In hybrid SWAC–OTEC configurations, the cold seawater used for electricity generation can subsequently be used for air conditioning, thereby extending the utility of the same thermal resource. Shared infrastructure, such as intake and discharge pipelines, further reduces capital and environmental costs. It aligns with the emerging paradigm of red chemistry, which advocates for low-impact and multi-benefit solutions tailored to both environmental protection and societal development [83]. It is particularly relevant for tropical islands, where the demand for these four resources is often urgent. By multiplying the services provided by the system, economic efficiency is not only increased but also contributes to the resilience and sustainability of the islands.

7. Comparative analysis of SWAC and OTEC with conventional and renewable alternatives

To assess the relevance and maturity of SWAC and OTEC technologies, it is essential to compare their performance with both conventional and renewable alternatives. Table 5 presents a comparative overview of

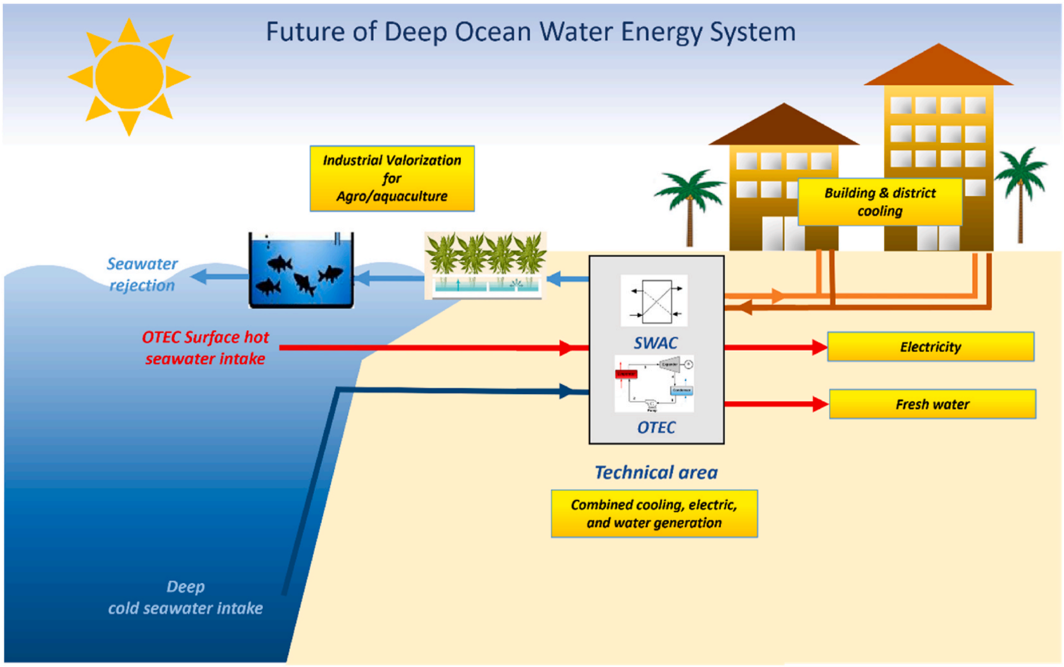

Fig. 11. Conceptual integration of SWAC and OTEC systems for multi-purpose applications (cooling, electricity, freshwater, and aquaculture).

Table 5
Comparative performance of SWAC/OTEC and conventional or renewable alternatives [11,16,84–86].

	System	Efficiency or Capacity factor	LCOE ($/MWh)	$\mathbf{CO_2}$ emission factor (kg $\mathbf{CO_2}$/MWh)
Cooling Production	**SWAC**	25	113.9	21–26
	Split system	3.5	/	150–180
	Chiller	6	182.4	80–100
Electricity Production	**OTEC**	1–3 %	200–400	28.5–42.8
	Solar (commercial)	18–24 %	74–140	18–180
	Offshore wind	40–50 %	49–200	8.0–35
	Tidal power	20–35 %	130–280	5.6–28
	Coal	30–40 %	75–110	820–1000
	Natural gas	20–35 %	42–107	400–500

key indicators such as efficiency (Coefficient of Performance for cooling or capacity factor for offshore wind and tidal energy), levelized cost of energy (LCOE), and carbon dioxide emission factor.

From this comparison, it is clear that SWAC demonstrates outstanding energy efficiency in cooling applications, far surpassing conventional systems such as split units or chiller-based air conditioning. Its low carbon footprint and acceptable LCOE further reinforce its relevance for sustainable cooling, especially in tropical coastal areas. For SWAC, the high CAPEX remains a major barrier, with investment costs ranging from €5.5M to €30M depending on system size. Nevertheless, lifetime energy savings are considerable: over a 30-year lifespan, breakeven can be achieved in about 10 years, making SWAC a profitable long-term solution [16].

Additionally, SWAC systems offer high scalability and could be deployed in large urban settings such as megacities, provided appropriate coastal conditions exist. Scaling up is technically straightforward, as it primarily involves increasing the diameter of the seawater intake pipeline to accommodate larger flow rates. Moreover, the higher the cooling demand, the more viable SWAC becomes economically, as the fixed infrastructure costs are better amortized over greater energy savings. Its massive cooling potential and low environmental impact make it a viable alternative to fossil-fuel-based air conditioning.

OTEC, while less mature than other renewable energy technologies, offers the distinct advantage of providing stable, continuous baseload power, operating day and night, regardless of weather conditions, unlike intermittent renewables like solar and wind. When it comes to costs, OTEC is currently not competitive with solar or wind power, although its LCOE remains high (200–400 $/MWh), it is not significantly higher than that of emerging marine technologies like tidal power. However, with improvements in component design and increased deployment, there is potential for cost reduction.

In terms of greenhouse gas emissions, OTEC systems produce very low operational CO_2 emissions, partly due to the release of dissolved CO_2 during deep seawater discharge. Estimates suggest that typical closed-cycle OTEC plants release approximately 28.5–42.8 gCO_2/ kWh of electricity produced [11], which is significantly lower than fossil fuel-based electricity generation, approximately 500 gCO_2/ kWh for natural gas and up to 1000 gCO_2/kWh for coal [85]. Although the amount of dissolved CO_2 released may vary by location and system design, it remains a minor contributor compared to direct combustion emissions. Moreover, when OTEC is coupled with freshwater and cooling production, the carbon benefit per unit of service increases even further, reinforcing its value as a low-carbon base-load energy option in tropical regions.

Despite the growing interest and the promising metrics presented, key research and development gaps remain. Table 6 summarizes these gaps and highlights avenues for future work to accelerate the deployment and optimization of DOW energy systems.

Table 6
Research gaps for SWAC and OTEC development.

Subject	Description
Heat Exchangers	Industrialization of cheaper alternative to titanium heat exchangers.
Pipeline conception	AI-based optimization tools to design seawater intake and discharge pipelines to reduce energy losses and mitigate biofouling risks.
Working fluid	Nanofluids or CO_2-based mixtures to enhance heat transfer and thermodynamic efficiency of OTEC systems.
Integrated systems	Need to develop integrated systems combining all individual technological advancements for multi-purpose applications.
Environmental impacts	Very few quantified environmental assessments and a lack of standardized methodologies.
Social acceptance	Very few studies and only for Hawaii. Need to raise awareness among populations on these technologies.

8. Conclusion

This article has provided an overview of deep seawater-based energy systems, highlighting their growing relevance in the current context of climate change and increasing energy demand. As the need for building cooling continues to rise, particularly in tropical regions, SWAC technology stands out as an innovative and sustainable solution to reduce dependence on non-renewable energy sources. Despite the successful deployments of real-life installations in French Polynesia, reinforced by various feasibility studies, there remains a lack of deployments worldwide, maintaining an uncertainty regarding the reliability and efficiency of this technology. Thus, the technical challenges and high initial costs associated with the technology continue to hinder its large-scale adoption. Nonetheless, existing projects provide compelling evidence of its potential: although investment costs remain high, ranging from €5.5 to €30 million in recent SWAC systems, the technology exhibits outstanding performance. Reported SCOP values exceeding 25 in recent installations highlight its superior energy efficiency compared to conventional air conditioning, reinforcing its relevance for long-term sustainable cooling in coastal areas.

At the same time, OTEC technology offers immense potential for uninterrupted renewable electricity production by harnessing the temperature difference between surface and deep waters. Real installations show that, despite still high costs, OTEC plants could become economically viable, particularly in regions where alternative energy sources are limited and expensive. These technologies can also be coupled with other mature renewable energy sources, such as photovoltaic solar or wind power, to optimize the overall energy yield and operational efficiency of the installations. Moreover, the potential synergy between SWAC, OTEC, and other systems, such as desalination and aquaculture, pave the way for integrated solutions with proven benefits. However, these couplings remain insufficiently studied, even though optimizing interactions between these systems could have a significant impact on energy efficiency and profitability by enabling better utilization of deep seawater resources. In fact, coupling SWAC and OTEC systems can enhance the overall efficiency and economic viability of deep ocean water energy infrastructures by enabling multi-use of the same intake infrastructure and thermal gradient. In such configurations, OTEC produces electricity using the temperature difference between surface and deep seawater, while SWAC directly uses the cold deep water for cooling purposes, without the need for a thermodynamic cycle. This dual usage allows for better utilization of the thermal potential of the resource: OTEC often leaves the cold seawater at a temperature still low enough for SWAC if district cooling temperatures are adjusted appropriately, allowing it to be used sequentially. Additionally, sharing the intake and discharge pipelines reduces capital costs. These hybrid systems are particularly suited to island regions, where simultaneous demand for electricity, cooling, and potentially desalination exists, maximizing the return on infrastructure investment and reducing environmental footprint per unit of service delivered.

The future of the Deep Ocean Water Energy System lies in the study and deployment of integrated systems that combine all individual technological advancements, as depicted in Fig. 11.

Furthermore, the environmental impacts and socio-economic considerations related to the implementation of these technologies remain largely unexplored. Potential impacts on marine ecosystems, though poorly quantified, appear to be relatively minor when measured and can be mitigated through appropriate measures. The social acceptance of these technologies will largely depend on raising awareness among local populations and their involvement in the decision-making process. It is, therefore, essential not to overlook research in these areas to ensure the sustainable and widely accepted deployment of these technologies.

In addition to technical, economic, and environmental aspects, the deployment of deep ocean water energy systems also depends on local policy and regulations, especially in island and coastal areas. Supportive measures, such as targeted financial incentives, concessional financing, and public-private partnerships, can significantly lower entry barriers for these capital-intensive projects. On the other hand, complex or fragmented permitting processes, especially for marine infrastructure, may delay implementation and increase costs. Streamlined environmental permitting, clear marine spatial planning, and the integration of deep ocean water technologies into broader energy and climate strategies are therefore essential. For small island contexts, strengthening institutional capacity and fostering regional cooperation can help overcome administrative barriers while still protecting the environment.

Beyond integrated deployments, future research should also focus on technological innovations to improve performance and reduce costs. One promising path is the use of advanced working fluids, such as nanofluids or CO_2-based mixtures, to enhance heat transfer and thermodynamic efficiency in OTEC systems. In parallel, AI-based optimization tools could be leveraged to design seawater intake and discharge pipelines, aiming to reduce energy losses and mitigate biofouling risks. Such innovations are essential to making deep ocean energy technologies more competitive, scalable, and resilient.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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