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Research Paper

Energy performance assessment of Sea Water Air Conditioning (SWAC) as a solution toward net zero carbon emissions: A case study in French Polynesia



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ABSTRACT

Sea Water Air Conditioning (SWAC) technology uses deep ocean water to cool buildings. It is a non-intermittent renewable thermal energy used directly without any transformation. It may replace other air-conditioning systems powered by electrical energy (mechanical vapor compression thermodynamic cycle) or powered by other renewable energies (solar heating and cooling systems). Despite its theoretical appeal as a solution to help achieve net-zero carbon emissions, and the existence of successful deployments, SWAC technology remains scarce worldwide mainly due to its investment cost (CAPEX). One reason for this failure to scale might be the absence of experimental data detailing energy performance of SWAC systems in real-world, commercial settings. Here is presented the performance of an existing 2.4 MW SWAC system, operated by The Brando resort on the atoll of Tetiaroa in French Polynesia. Under a tropical climate, experimental results show that the Coefficient of Performance (COP) of the SWAC system can reach 20 to 150 depending on the secondary loop length, compared with conventional vapor compression systems that peak at around 5 for the most efficient. To put this in terms of carbon emissions avoided, conventional unitary split systems running in similar hotels on neighboring islands in French Polynesia (COP around 3.5) emit some 860 Tons/year compared to the estimated 225 Tons/year emitted (approximated with the emissions factor of French Polynesia in 2019) operating the Tetiaroa SWAC.

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1. Introduction

1.1. Conventional air conditioning

Cooling of buildings with conventional air conditioning (AC) technology has been widespread in developed countries in the late 20th century, and is becoming increasingly common in countries with hot climates and large populations, such as India and China (Goetzler et al., 2016). According to the International Energy Agency (IEA) report (International Energy Agency (IEA), 2018), the energy consumption induced by the cooling needs of buildings tripled between 1990 and 2016, becoming the most rapidly increasing source of energy demand. In another report, the IEA predicts that this upward trend is likely to continue: for

the period 2010 through 2050, energy demand for AC is expected to multiply by 1.3 for Organization for Economic Co-operation and Development (OECD) countries and by 4.5 for others (International Energy Agency (IEA), 2013). Constantly increasing demand puts huge technical constraints on the electrical grids of tropical regions, with AC responsible for ~70% of buildings' peak power demand. Furthermore, AC has a strong environmental impact with tripled carbon dioxide emissions since 1990, reaching 1130 million tons per year in 2016 (International Energy Agency (IEA), 2018). Conventional AC also uses HFCs refrigerants which are potent greenhouse gases (International Energy Agency (IEA), 2020). The solutions to reduce AC's electric consumption fit into two different categories: energy conservation and energy efficiency. Energy conservation involves all the habits allowing a more reasonable use of air conditioning, from raising users' awareness of energy saving usage to the very conception of buildings. Energy efficiency consists in improving the performance of air conditioning systems, commonly estimated by the Energy Efficiency Ratio (EER) or Coefficient of Performance (COP), which

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is the cooling energy divided by the electric energy consumed by the system in defined operating conditions. The SWAC technology (Sea Water Air Conditioning) offers an efficient alternative to conventional air conditioning for coastal zones with access to cold deep ocean water, which could be an inexhaustible refrigeration source.

1.2. Sea Water Air Conditioning: State of the art

Most scientific papers dealing with SWAC technology have a modeling approach to estimate its performance and cost. [Hunt et al. \(2019\)](#) concludes that the potential of SWAC is huge especially in intertropical regions with small islands because of their high electricity costs and favorable bathymetry, allowing the seawater intake pipeline to be shorter and its price is therefore reduced. [Hernández-Romero et al. \(2019b,a\)](#) developed a multi-scenario model for a touristic zone in Mexico to determine the optimal design of a SWAC system according to the different stakeholders involved and the weights of each.

Other articles focus on estimating the potential of Deep Ocean Water (DOW) itself, which can provide electricity, freshwater, and nutrients for aquaculture or cosmetics in addition to cooling. A case study in San Andrés Island describes a system combining Sea Water Air Conditioning (SWAC) and Ocean Thermal Energy Conversion (OTEC) with a desalination stage, which can operate independently or in cascade ([Osorio et al., 2016](#)). Moreover, a methodology was developed to estimate the practical potential of DOW applied to five Caribbean cities, however there is lack of knowledge regarding the real potential of DOW based on operating installations ([Arias-Gaviria et al., 2020](#)).

Operating variants of SWAC installations are also explored like Deep Seawater Cooling and Desalination (DSCD) systems. It consists of a SWAC paired with reverse osmosis desalination, allowing to provide water supply in addition to cooling power. Furthermore, those installations has a seawater return temperature of 15 to 18 °C compared to the 13 to 15 °C return of standard SWAC systems, less cooling potential is wasted ([Hunt et al., 2021](#)). A variant called high velocity SWAC with an excavation depth of 20 m for seawater pumps instead of 2 to 5 m is considered to prevent cavitation, especially if the seawater intake pipe is very long (10 to 20 km). This SWAC operates with intermittent renewable energies and combined with thermal energy storage to allow its operation to vary with the availability of renewable energy sources ([Hunt et al., 2020](#)).

Following a social science approach, some publications study the adoption of this technology by the population, which remains unknown to the public. [Lilley et al. \(2015\)](#) shows that Hawai'i people generally supports SWAC but is quite unfamiliar with it compared to solar or wind energy. [Arias-Gaviria et al. \(2018\)](#) and [Arias-Gaviria \(2019\)](#) focus on the case study of Caribbean islands through simulations. They indicate that the main limitation of its development is not related to the cost effectiveness of the technology (very low OPEX compared to conventional AC systems) but rather the lack of confidence in it, which is exacerbated by its high initial investment cost (CAPEX).

This lack of confidence can be overcome by presenting examples of successful SWAC installations operating in real-world, commercial settings. These installations are demonstrating the maturity of the technology and thus, its suitability for other coastal regions should be promoted, especially in tropical climate where cooling needs generates high energy demand and severe constraints on isolated electrical grids.

To sum up, there are currently no scientific publications describing the performance of a real SWAC system based on experimental measurements. The current value used for the SWAC global COP is 13 from a pre-feasibility study in the Caribbean

([Hunt et al., 2019](#)). In terms of research interest, having such feedback is necessary to validate the modeling work done and to allow a quicker adoption of SWAC by presenting a real operating installation demonstrating the great performance of the technology compared to conventional air conditioning systems. This is the aim of this article.

2. Methodology

2.1. The SWAC operating process

The SWAC technology consists in pumping naturally cold sea water through a pipeline. The sea water goes through a heat exchanger to give its cooling power to a chilled water loop that distributes the cooling energy to the air-conditioned building. The thermodynamics second law limits of conventional refrigeration cycles do not apply to SWAC, since the electric energy is used to transport cold water in liquid phase instead of transferring heat from a cold source to a hot source.

The SWAC system is composed of three parts ([Fig. 1](#)):

- The Sea Water (SW) loop, also named the primary loop, includes a deep drawing pipeline going down to about 1000 m and a shallower rejection pipeline at about 20 m depth. The inlet sea water temperature is around 5 to 7 °C and 11 to 13 °C for the outlet ([Makai Ocean Engineering and VanRyzin, 2004](#)).
- The Chilled Water (CW) loop, also named the secondary loop, is the freshwater system supplying the building with cold. The inlet chilled water temperature is usually set to 7 °C and 12 °C for the outlet.
- The technical area, containing one or several pumps for each water loop and heat exchangers between the SW loop and the CW loop.

2.2. The SWAC situation in the world

In 2016, only 5 SWAC installations were in operation with those located in Goseong, South Korea ([Korea Research Institute of Ships & Ocean Engineering \(KRISO\), Korea Institute of Ocean Science and Technology \(KIOST\), 2014](#)), Okinawa, Japan ([Okinawa Prefecture Department of Labor Commerce and Industry, 2013–2022](#)), and North Kona District, Hawaii ([Negara and Koto, 2017](#)) made to study OTEC cycles to produce electricity from the temperature difference between deep water and shallow water. Those made solely for their air-conditioning function were operated by hotels in tropical environments on Bora Bora and Tetiaroa in French Polynesia. In addition to SWAC, similar technology has been deployed in temperate climates using water from lakes, such as installations cooling a group of tertiary buildings Toronto, Canada, and Amsterdam, the Netherlands ([Osorio et al., 2016](#)), and from rivers, such as the Climespace system that draws chilled water from the river Seine in Paris, France.

All these systems employ a centralized cooling production, combined with a chilled water system called District Cooling (DC). The District Cooling seems more efficient than rooftop unit systems (RTU) or variable refrigerant flow (VRF) with, respectively, 55% and 18.4% reduction in energy consumption yearly according to [Alajmi and Zedan \(2020\)](#).

Research related to SWAC is sometimes linked to OTEC projects such as the on-land prototype in Saint-Pierre, Reunion Island, where several technologies of heat exchangers have been tested regarding the evaporator and the condenser of the Organic Rankine Cycle (ORC) ([Praene et al., 2012](#)). Studies of OTEC in Colombia ([Devis-Morales et al., 2014](#)) to meet electric demand have also addressed additional benefits of cold and nutrient rich deep ocean water including for cooling (SWAC) and for

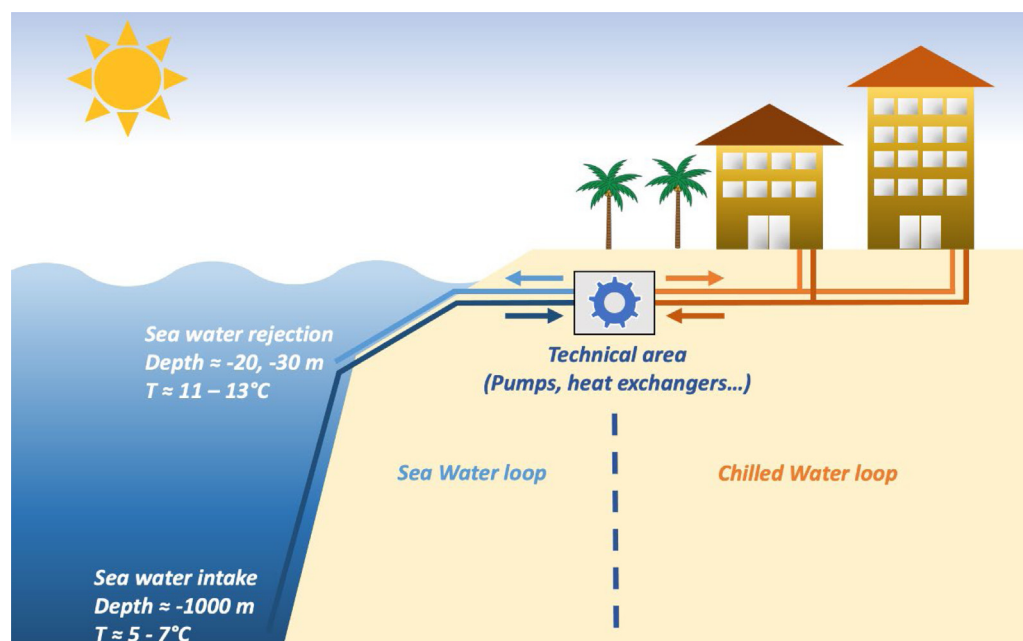


Fig. 1. Operating process diagram of the SWAC system.

Table 1

Characteristics of the different SWAC in French Polynesia.

Location	Year	Building type	Drawing depth	Drawing pipeline length	Drawing pipeline diameter	Cooling power
Bora Bora	2006	Hotel	−915 m	2300 m	400 mm	1.6 MWf
Tetiaroa	2011	Hotel	−960 m	2618 m	368/383 mm	2.4 MWf
Tahiti	2022	Hospital	−900 m	3800 m	710 mm	6 MWf

aquaculture (Takahashi and Ikeya, 2003). Finally, despite this technology being used ideally in areas with great depths close to the shore (Deep SWAC), it remains worth considering at other depths (Shallow SWAC) in regions where there are cold marine currents and/or in combination with an additional refrigeration unit (Osorio et al., 2016).

Even though SWAC is an efficient and cleaner alternative to regular air conditioning, the technology has not yet taken-off globally. A lack of knowledge about SWAC compared to other renewable energies might explain the slow uptake according to Lilley et al. regarding Hawaii (Lilley et al., 2015) and Arias-Gaviria et al. for the Caribbean (Arias-Gaviria et al., 2018).

SWAC in French Polynesia

The goal of the work described here was to carry out the first detailed experimental assessment of an operational SWAC. The study was carried out in French Polynesia, which has pioneered the commercial deployment of SWAC technology, beginning in the tourism sector and now serving the country's major public hospital (see Table 1).

Tahiti and the other islands of French Polynesia are well-suited for SWAC thanks to the steep drop-off to more than 900 m close to the coast, allowing relatively easy access to deep ocean water at about 5 °C. The first SWAC in French Polynesia was developed by Pacific Beachcomber SA for the Intercontinental hotel in Bora Bora in 2006. The installation was not instrumented when implemented, thus, its performance is not known precisely.

Pacific Beachcomber SA installed a second SWAC at The Brando hotel on the atoll of Tetiaroa in 2011, which we have instrumented, and the performance metrics are presented here.

The SWAC of the general hospital of French Polynesia (CHPF) is operational since July 2022 with instrumentation and report on its performance are expected in the near future.

Although the drawing depth is about the same for the three installations, the drawing pipeline length are quite different because of the differences in bathymetry, ranging from 2300 m for Bora Bora, to 3800 m for Tahiti.

2.3. The Brando SWAC installation

The Brando hotel is in the atoll of Tetiaroa situated 53 km away from Tahiti, it has a 6 km² surface area divided into 12 islets and is part of the Society Islands. Located at 17°S in the South Pacific, the atoll of Tetiaroa enjoys a tropical climate, with a wet and warm season from November to April and a dry and cold season from May to October. Laurent et al. provide charts displaying long term mean of maximum and minimum temperatures from the Meteo France in situ station of Tetiaroa. Long term average of daily maximum temperature ranges from 27.5 °C in August to 30.4 °C in March. Long term average daily minimum temperature ranges from 22.3 °C in August to 24.2 °C in March. As of insolation duration, the long-term annual mean reaches 2700 h (Laurent and Maamaatuaiahutapu, 2019). The hotel occupation is on average 30% of its full capacity over the year, with a peak during the warm season. The Brando SWAC installation is described below (Fig. 2):

This SWAC system is composed of a 2618 m drawing pipeline and an 865 m rejection pipeline, three primary pumps, three heat exchangers, three secondary pumps, and 3 km of District Cooling serving the hotel.

The drawing and rejection pipelines are made of high-density polyethylene (HDPE) to ensure a long lifespan and resistance to corrosion. They were fixed in a trench dug in the lagoon (Fig. 3), with care taken to transplant the corals to the sides of the trench. The drawing pipeline reaches a depth of 960 m, its diameter is 383 mm for the first 1618 m and 368 mm for the rest. The

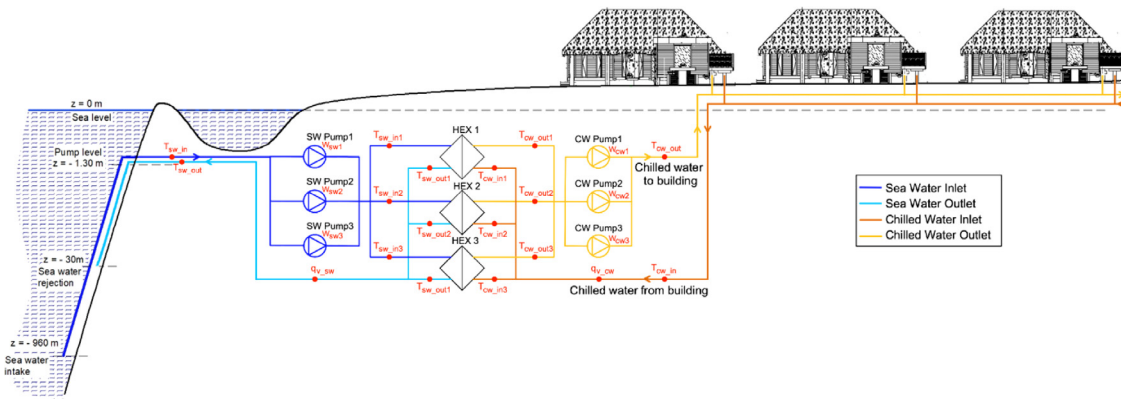


Fig. 2. Detailed diagram of Tetiaroa SWAC system and its instrumentation.



(a)



(b)

Fig. 3. Lagoon trench seen from sky (a) and arrangement of Tetiaroa pipeline (b).



Fig. 4. Plate heat exchanger.

rejection pipeline is 368 mm in diameter and releases the sea water back into the ocean at -30 m.

The three heat exchangers (Fig. 4) are always operating except during maintenance. These are counterflow titanium plate heat exchanger, each one has an exchange surface area of 207 m^2 and thermal power of 1201.67 kW for a rated flow of $210 \text{ m}^3/\text{h}$.

The installation is conceived to work with one or two variable speed pumps at once, a third pump is available during maintenance or failure. Each primary pump (Fig. 5a) is centrifugal with a rated capacity of $210 \text{ m}^3/\text{h}$, an electric power of 13.29 kW and an efficiency of 70.5% , with a 16 m rated head. They are made of stainless steel (316 SS) for casing, impeller, shaft sleeve and alloy steel (SAE 4140) for the shaft itself. Secondary pumps (Fig. 5b) are also centrifugal, their rated capacity, electric power, efficiency, and head are respectively of $140 \text{ m}^3/\text{h}$, 45 kW , 76.3% and 80 m .

Table 2

Uncertainty in measurements of Brando SWAC instrumentation.

Instrument	Uncertainty
Temperature probe PT100 (Class A)	$\pm 0.08\%$
Ultrasonic flowmeter	$\pm 3\%$
Spinner flowmeter	$\pm 5\%$
SW Electricity meter	$\pm 1\%$
CW Electricity meter	$\pm 1\%$

They are made of gray cast iron (EN GJL 250) for casing, impeller, and stainless steel (X20Cr13) for the shaft and its sleeve.

The instrumentation includes 16 PT100 temperature probes placed at inlets and outlets of each heat exchanger and loop. Sea and chilled water flow rates are measured through an ultrasonic flowmeter (KHROME Optisonic 6300) for the primary and a spinner flowmeter (BMETERS GSD5) for the secondary. Finally, the pump electric powers are measured by three-phased electricity meters (Schneider Electric IEM3250 for SW pump and AEM3555 for CW pump). All these instruments were installed in February 2021, their locations are shown in Fig. 2 and their uncertainties in Table 2.

The chilled water loop (District Cooling) is around 3 km long (Fig. 6), and supplies the whole hotel, including staff quarters and technical buildings, with cold via 2 pipes (in/out). The hotel has 30 single bedroom villas; 4 two-bedroom villas and one three-bedroom villa (Fig. 7), which makes a total of 35 villas distributed around the coastline. The air is chilled by a cooling coil supplied by the CW loop and blew into the room through an air vent.

In the northern part of the island (Fig. 6), there is the airport, technical facilities, and staff quarter, as well as a field station built by Pacific Beachcomber and operated by its partner non-profit



Fig. 5. Primary pump (a) and secondary pump (b).

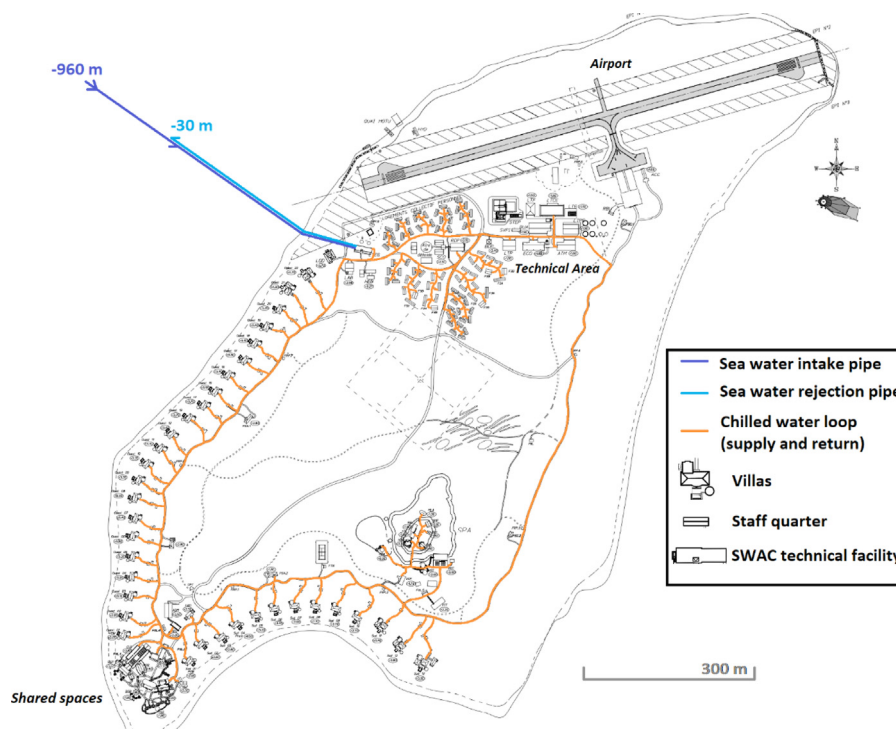


Fig. 6. Ground plan of The Brando chilled water loop.

organization ‘Tetiaroa Society’ that includes a marine laboratory plumbed with flowing seawater from the SWAC (deep ocean water) as well as from the sea surface. Shared spaces like restaurants and relaxation areas are grouped in the south-west part of the island. The whole is equivalent to an air-conditioned surface area of around 7000 m²

Additional residences are planned for the eastern coast along the CW loop and so the SWAC is oversized for its current needs, being designed to meet the cooling demand of the final build-out envisaged in the hotel master plan.

3. Results and discussions

3.1. Experimental analysis over a short period

To assess the performance of the Tetiaroa SWAC installation, experimental results over a short period are presented and analyzed, from July 10 to July 21, 2021. The objective is



Fig. 7. Three-bedroom villa.

to undertake a detailed experimental study on all the different components of the installation to confirm the instrumentation

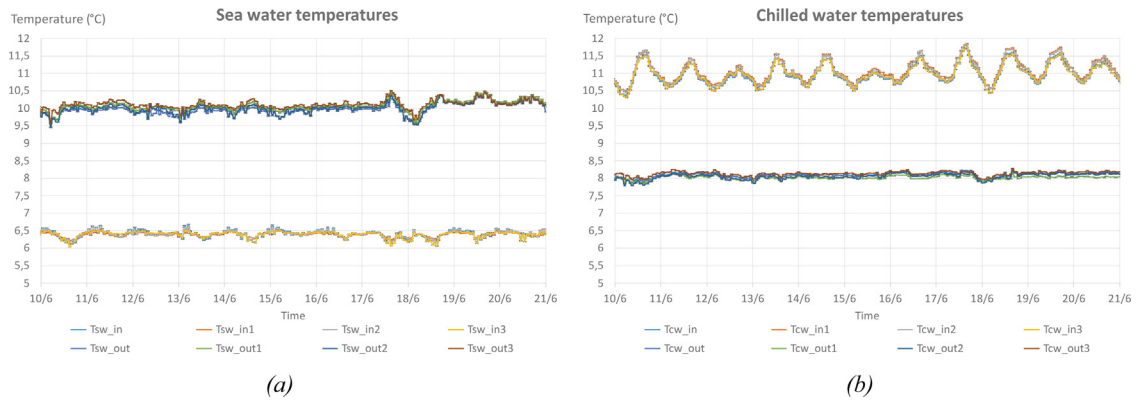


Fig. 8. Evolution of sea water temperatures (a) and chilled water temperatures (b).

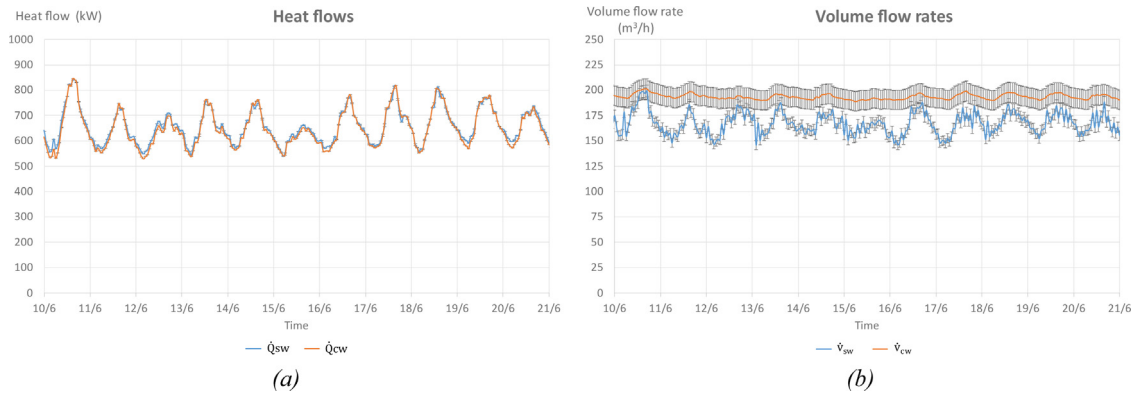


Fig. 9. Evolutions of sea water and chilled water heat flows (a) and volume flow rates (b).

reliability and estimate the Coefficients of Performance (COP) of the SWAC system.

The curves of the four sea water temperatures at the heat exchanger inputs (Fig. 8a: T_{sw_in}, T_{sw_in1}, T_{sw_in2}, T_{sw_in3}) have the same shape with quite stable values between 6 and 6.5 °C throughout the studied period. Regarding the sea water temperatures at the heat exchanger outputs (Fig. 8a: T_{sw_out}, T_{sw_out1}, T_{sw_out2}, T_{sw_out3}), they fluctuate around 10 °C, remaining between 9.5 °C and 10.5 °C.

Concerning the chilled water temperatures at the heat exchanger outputs (Fig. 8b: T_{cw_out}, T_{cw_out1}, T_{cw_out2}, T_{cw_out3}), these are not time dependent and stay equal to approximately 8 °C. As this temperature is regulated to reach an 8 °C setpoint by varying the sea water flow rate with a regulator connected to the sea water pumps. On the other hand, chilled water temperatures at the heat exchanger inputs (Fig. 8b: T_{cw_in}, T_{cw_in1}, T_{cw_in2}, T_{cw_in3}) vary distinctly from 10.3 to 11.8 °C. This is the consequence of the cooling demand variability (Fig. 9a: Q_{cw}), which is higher during the day with peak at 850 kW leading to an increased return temperature from the chilled water loop. During the studied experimental period, the occupation rate of air-conditioned buildings was nearly constant over time, with a periodically stable variation in cooling demand between 550 kW at night and 850 kW during the day.

Heat flows in the sea water side (Q_{sw}) and chilled water side (Q_{cw}) are described in Fig. 9a and calculated according to the Eq. (1). Thermo-physical properties of sea water are determined from the work of Sharqawy et al. (2010) and Nayar et al. (2016).

$$\begin{aligned} \dot{Q}_{sw} &= \rho_{sw} \cdot \dot{V}_{sw} \cdot c_{p,sw} \cdot (T_{out,sw} - T_{in,sw}) \\ \dot{Q}_{cw} &= \rho_{cw} \cdot \dot{V}_{cw} \cdot c_{p,cw} \cdot (T_{in,cw} - T_{out,cw}) \end{aligned} \quad (1)$$

Heat flow is similar on the sea water side (Q_{sw}) and chilled water side as heat exchanger loss are negligible compared to the cooling powers involved (between 550 and 850 kW). In the same way as heat flows, sea water and chilled water volume flow rates (Fig. 9b) have the same periodically stable shape, with flow rates between 150 and 200 m³/h for sea water and from 190 to 200 m³/h for chilled water. The sea water volume flow rate has greater variations to make up for the cooling demand decrease during night and stabilize the chilled water loop inlet temperature to the 8 °C setpoint.

Electrical powers and daily energies of sea water and chilled water pumps are plotted in Fig. 10a and b. Given the cooling demand level (Q_{cw} ≈ 15 000 kWh, Fig. 10b), only a single pump of each loop is required throughout the whole experimental sequence. While sea water pump n°1 is on (from June 10 to 12), chilled water pump n°1 is on as well. This also applies to pumps n°2 (from June 12 to 18) and n°3 (from June 18 to 21). Every week, the machine operator changes the operating pumps to balance their running time throughout the year. The electrical power consumed by chilled water pumps remains steady at about 35 kW meanwhile the sea water pumps varies between 3 and 5 kW to maintain the required cooling power (Fig. 9a: Q_{cw}). The District Cooling accounts for 87.5% of the electricity consumed by the SWAC installation against 12.5% for the sea water loop.

The installation efficiency is estimated with the primary COP, the global COP (Fig. 11a), they are calculated with the Eq. (2). Heat exchanger efficiencies are plotted as well (Fig. 11b).

$$\begin{aligned} COP_{prim} &= \frac{\int_0^t \dot{Q}_{cw} \cdot dt}{\int_0^t \dot{W}_{sw} \cdot dt} \\ COP_{glob} &= \frac{\int_0^t \dot{Q}_{cw} \cdot dt}{\int_0^t \dot{W}_{sw} \cdot dt + \int_0^t \dot{W}_{cw} \cdot dt} \end{aligned} \quad (2)$$

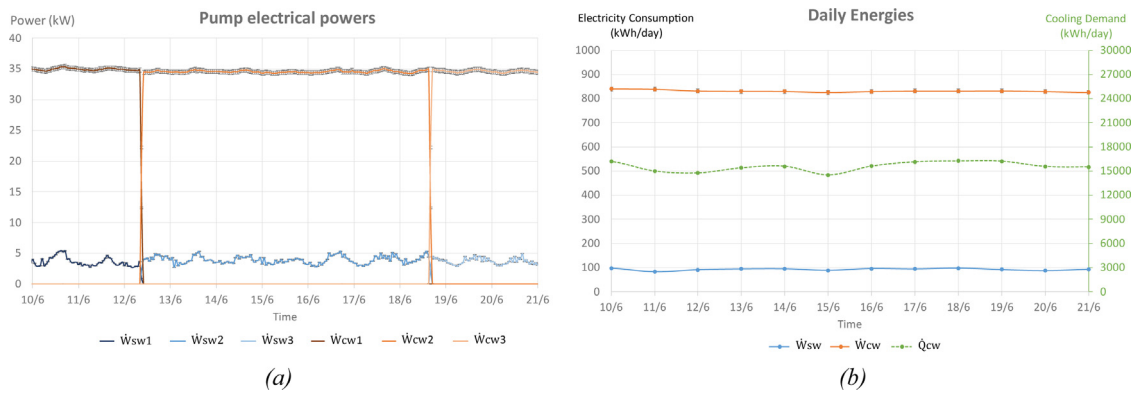


Fig. 10. Evolutions of pump electrical powers (a) and daily energies (b).

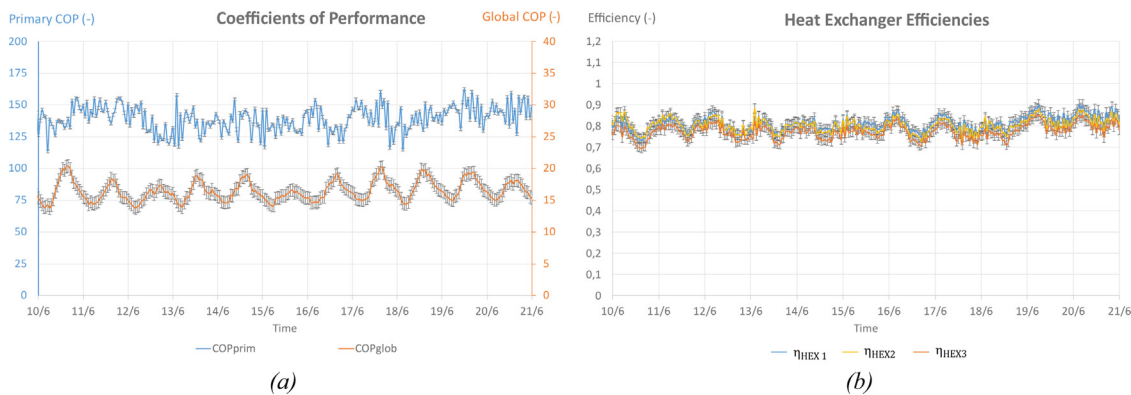


Fig. 11. Evolutions of primary and global COP (a) and heat exchanger efficiencies (b).

Counterflow heat exchanger efficiency (η_{HEX}) is defined like this (Incropera et al., 2007) :

$$\eta_{HEX} = \frac{\dot{Q}_{cw}}{(\dot{q} \cdot \dot{v} \cdot cp)_{\min} \cdot (T_{in_cw} - T_{in_sw})} \quad (3)$$

with $(\dot{q} \cdot \dot{v} \cdot cp)_{\min} = \min(\dot{q}_{sw} \cdot \dot{v}_{sw} \cdot cp_{sw} ; \dot{q}_{cw} \cdot \dot{v}_{cw} \cdot cp_{cw})$

The primary COP varies between 120 and 160 with an average value of around 140. These values are a lot higher than those reached by conventional vapor compression systems which peak around 5 for the most efficient (International Energy Agency (IEA), 2018). The global COP stays between 15 and 20 with an average at 17, which is still 3 to 4 times higher than conventional air conditioning systems. The huge electric consumption of secondary pumps induced by the large, chilled water loop leads to an COP decrease by a factor of 8.

Lastly, the efficiencies of the three heat exchangers (Fig. 11b: η_{HEX}) have the same shape with values between 70 and 90%, which seems correct for this type of plate heat exchanger (Incropera et al., 2007).

3.2. Experimental analysis over a long period

The graphs of the daily electric consumption of sea water and chilled water loop, the daily cooling demand and the two COP are presented from April 2018 to July 2021 (Figs. 12 and 13). For a better understanding of the installation’s operation and to analyze its performance, several experimental sequences (from A to E) are shown. It should be noted that the SWAC installation was in maintenance from March to May 2021, explaining the lack of experimental data for this period (Grayed zone in Figs. 12 and 13)

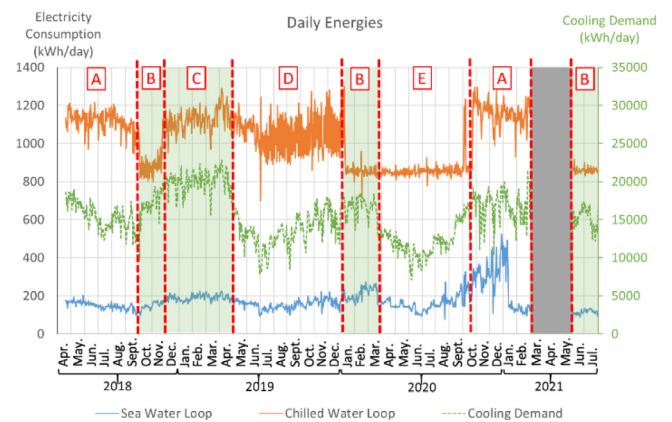


Fig. 12. Evolutions of daily energies with several studied periods over a long period.

During the first experimental sequence (A), a single pump was operating in SW loop and two pumps at once in CW loop, leading to average daily consumption of 175 kWh/day for the primary and 1150 kWh/day for the secondary. The cooling demand was gradually decreasing from 18 000 kWh/day in April 2018 to 13 000 kWh/jour in September 2018. This decrease in cooling demand caused a reduction of the global COP, which went from 13.6 in April to 10.3 in September with an average of 12.2 during this period. The primary COP remained quite stable with values between 90 and 110. A similar experimental sequence (A) was observed between October 2020 and February 2021 when global COP was approximately the same. But the electric consumption of sea water pumps was way higher than in the first sequence A

Table 3
Typical extremum values of COP and minimum Emission Factor for different AC systems.

Available commercial ACs	Minimum COP	Maximum COP	Minimum Emission Factor for cooling (gCO ₂ /kWh)
SWAC	10 (With district cooling)	150 (Without district cooling)	50.4
Chillers	3	12	168
VRF multi-split	3	10	168
Large packaged AC	2.5	7	201.6
Large split AC	3	5	168

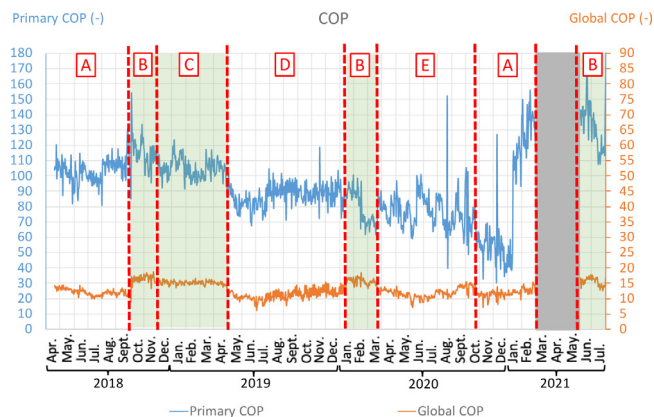


Fig. 13. Evolutions of primary and global COP with several sequences over a long period.

due to a regulation issue that caused the operation of two pumps at a very low level of output (50% of rated) instead of one pump at rated speed. Performance drastically drops when a pump operates at only 50% of its rated speed (Delgado et al., 2019).

Given the low cooling demand value in September 2018 ($\dot{Q}_{cw} < 13\,000$ kWh/jour), the operating mode was changed to one chilled water pump and one sea water pump in the experimental sequence B from October to November 2018. During this period, the electric consumption stabilized at an average of 830 kWh/day for the secondary loop and 150 kWh/day for the primary loop. Then, the cooling demand increased gradually from 15 000 kWh/day in early October to 20 000 kWh/day late November 2018. Under these circumstances, the global COP increased compared to sequence A to reach a mean value of 16.2, with a primary COP at 110. The same performance was repeated later (sequences B) between January and March 2020, as well as June and July 2021, with global COP higher than 15.

Therefore, the operation mode with a single chilled water pump is the most efficient for a cooling demand lower than 20 000 kWh/day. Whenever this threshold is crossed, two chilled water pumps should start simultaneously, as in December 2018 (beginning of the sequence C). During this sequence, from December 2018 to April 2019, the cooling needs were fluctuating around 20 000 kWh/day with average electric consumptions of 190 kWh/day for the SW loop and 1100 kWh/day for the CW loop. In this case, the SWAC performance are quite good with COP of 105 for the primary and 15.5 for the global.

In May 2019, the cooling demand decreased drastically, dropping below 10 000 kWh/day in June 2019 with the experimental sequence D (May to December 2019). Even though the operating mode stayed the same with two chilled water pumps running leading to a significant reduction of both COP to 90 for the primary and 10 for the global COP, which is still far better than regular AC systems ($EER_{glob} = 5$). It would have been even better, however, to have run on a single chilled water pump to maintain the good performance achieved in sequence C.

Lastly, in the period between April and September 2020 (sequence E), the austral winter and usually high season for tourism

in French Polynesia, the cooling demand was very low due to the COVID-19 crisis during which the hotel was closed. Under these circumstances, only one pump was operating in the CW loop. The COP varied between 60 and 90 for the primary, and from 10 to 15 for the global.

Fig. 14a and b present the primary and global COP as a function of the cooling demand. A linear tendency is observed for both graphs, even more distinct for the global COP. By relying on these data, a minimum limit for global COP can be defined according to the cooling demand, this limit allows to verify if the installation is operating properly. The annual average COP of SWAC and its minimum Emission Factor (for Tahiti) compared to conventional systems (calculated for: outside temperature of 35 °C, inside temperature of 27 °C, and relative humidity of 50%) (International Energy Agency (IEA), 2018) are summarized below (see Table 3).

4. Conclusions and future work

The Brando SWAC installation can reach primary COP of 140 to 150 and global COP of 15 to 20. The difference between these COP is explained by the significant electric consumption of the chilled water pumps, which is approximately 7 times higher than that of the sea water pumps because of the wide spatial distribution required by the resort District Cooling.

Despite the water system size and a few operating issues, the performance of the SWAC installation remains very attractive compared to regular air conditioning systems with global COP always greater than 10 over more than 3 years of data. According to the IEA report, the COP of a unitary “large split AC” system is at most 5 (compared to the global COP) and that of a centralized “chiller” system is 12 (compared to the primary COP because it also includes a distribution loop). Knowing that in general, “global best available technology is more than twice as energy efficient as market averages and more than three times more efficient than the most inefficient models currently available” (International Energy Agency (IEA), 2018).

Experimental results reveal that the installation can operate properly with a single pump in each loop for a cooling demand lower than 20 000 kWh/day. After this limit, two pumps are required on each side.

The following hypothesis can be ventured: the global COP of SWAC installation in conjunction with a single building instead of a District Cooling will be closer to the primary COP of The Brando’s SWAC. It will be interesting to test this hypothesis with the SWAC operating in the general hospital of French Polynesia.

The SWAC technology has the benefit to not emit any fluorinated gas which has a significant environmental impact. The SWAC can be established as a sustainable and efficient solution to decarbonize cooling production in many locations, including tropical areas with a high average CO₂ emission factor such as French Polynesia (504 gCO₂/kWh in 2019 (Observatoire Polynésien de l’Énergie (OPE), ADEME, 2019)). SWAC system emits 3 to 4 times less CO₂ than other technologies for cooling production according to their minimum COP. Similar hotels in French Polynesia with several bungalows spread out along the beach mostly operates with large split systems (with an average COP of 3.5) to avoid the use of a District Cooling. An hotel like The Brando would emit

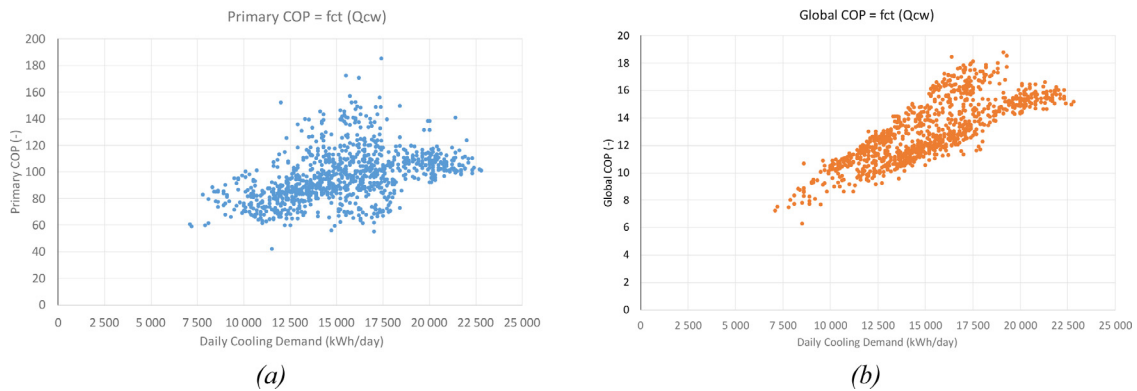


Fig. 14. Evolutions of primary (a) and global (b) COP according to the cooling demand.

some 860 Tons/year using regular large split systems compared to the estimated 225 Tons/year emitted (approximated for 2019 in Tahiti) operating the Tetiaroa SWAC.

The electric consumption of the chilled water pumps is the main factor to reduce in order to increase the global COP of the installation. The secondary flowrate is controlled by a pressure setpoint. According to the chilled water return temperature which remains quite cold (10,5 °C) compared to the regular thermostat setpoint (25 °C), this flowrate can be decreased allowing energy saving. More efficient control on district cooling pumps should be investigated to make the most of SWAC technology.

In future work, these experimental data will allow us to verify a mathematical model of SWAC system with high accuracy. Economic data must be collected as well, and included in this model, thus laying a theoretical foundation for the promotion of SWAC technology in the future. This model will be used to consider operating variants with the main objective of optimizing its energy performance and reducing its investment cost. A sensitivity analysis on the secondary temperatures (from 7/12 °C to 11/17 °C) would be interesting to consider a shallower drawing point involving a shorter seawater pipeline and thus a reduced cost.

Nomenclature

cp	Heat capacity ($J\ kg^{-1}\ K^{-1}$)
P	Pressure (bar)
\dot{Q}	Cooling power (W)
\dot{v}	Volume flow rate (m^3/s)
T	Temperature (°C)
\dot{W}	Electric power (W)

Greek symbols

η	Efficiency
ρ	Density (kg/m^3)

Indices

1	Pump/Heat exchanger n°1
2	Pump/Heat exchanger n°2
3	Pump/Heat exchanger n°3
CW	Chilled Water
glob	Global
HEX	Heat Exchanger
in	Input
out	Output
prim	Primary
SW	Sea Water

Acronyms

CAPEX	Capital Expense
COP	Coefficient of Performance
DC	District Cooling
DSCD	Deep Seawater Cooling and Desalination
EER	Energy Efficiency Ratio
HFCs	Hydrofluorocarbons
OPEX	Operating Expense
OTEC	Ocean Thermal Energy Conversion
HDPE	High-density Polyethylene
SWAC	Sea Water Air Conditioning

CRediT authorship contribution statement

Kanhan Sanjivy: Methodology, Investigation, Writing – original draft. **Olivier Marc:** Methodology, Writing – original draft, Visualization. **Neil Davies:** Writing – review & editing. **Franck Lucas:** Conceptualization, Supervision, Project administration, Funding acquisition.

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.

Data availability

The authors do not have permission to share data.

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