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Published in:
Energy Efficiency

DOI (link to publication from Publisher):
10.1007/s12053-020-09905-0

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Hunt, J. D., Zakeri, B., Nascimento, A., Garnier, B., Pereira, M. G., Bellezoni, R. A., de Assis Brasil Weber, N., Schneider, P. S., Machado, P. P. B., & Ramos, D. S. (2020). High velocity seawater air-conditioning with thermal energy storage and its operation with intermittent renewable energies. *Energy Efficiency*, *13*(8), 1825-1840. https://doi.org/10.1007/s12053-020-09905-0

Energy Efficiency (2020) 13:1825–1840
https://doi.org/10.1007/s12053-020-09905-0

ORIGINAL ARTICLE

High velocity seawater air-conditioning with thermal energy storage and its operation with intermittent renewable energies

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Received: 23 December 2019 / Accepted: 1 October 2020 / Published online: 17 October 2020

Abstract The rapid increase in cooling demand for air-conditioning worldwide brings the need for more efficient cooling solutions based on renewable energy. Seawater air-conditioning (SWAC) can provide base-load cooling services in coastal areas utilizing deep cold seawater. This technology is suggested for inter-tropical regions where demand for cooling is high throughout the year, and it has been implemented in islands with short distances from the coast and the deep sea. This paper proposes adjustments to the conventional design of SWAC plants to reduce implementation risks and costs. The approach is named high velocity SWAC and consists of increasing the excavation depth of the seawater pump station up to 20 m below the sea level, compared to 2 to 5 m in conventional SWAC projects. This allows a twofold increase in the speed of inlet pipeline seawater and cooling load of the plant. The cooling load can be expanded twofold with only 55% capital cost and 83% project costs, compared with the costs of a new system. In addition, this article shows that high velocity SWAC plants with thermal energy storage will have an important role supporting the dissemination of intermittent renewable sources of energy in regions where SWAC is a viable cooling alternative.

Highlights
- Detailed description of SWAC plants.
- Considerable reduction in capital and operation costs, and risk of SWAC projects.
- The cooling load can be expanded twofold with only 55% capital cost and 83% project costs,
- Cheap alternative to store energy from intermittent renewable sources.

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Keywords Building refrigeration · Cooling demand · District cooling · Energy efficiency · Seawater air-conditioning

Introduction

World demand for air-conditioning is surging rapidly due to life quality improvement in developing countries and global warming. The Intergovernmental Panel on Climate Change (IPCC) estimates that demand for residential air-conditioning alone will rise from 300 terawatt hours per year (TWh/year) in 2000 to 4000 in 2050 and 10,000 by 2100 (Henley 2015). Other estimates predict that demand for cooling is set to surpass heating around 2070, as shown in Fig. 1 (Isaac and van Vuuren 2009). Energy costs can be very high for air-conditioning systems, especially in island locations, where electricity costs are usually high due to the reliance on liquid fossil fuels as the main generation resource.

The deep ocean, located beneath the thermocline, is an almost unlimited heat sink (cooling source) that creates an opportunity to develop lower cost district cooling systems near the sea. Seawater air-conditioning (SWAC) is a district cooling technology that uses deep cold seawater for cooling that can be as cold as 3–5 °C at depths between 700 and 2000 m, even in the tropics (National Oceanic and Atmospheric Administration 2018), as shown in Fig. 2. The difference in temperature between surface and deep ocean have been extensively studied for electricity generation and desalination purposes (Khosravi et al. 2019; Jung and Hwang 2014; Semmari et al. 2012; Odum 2000).

SWAC started to be considered in the 1970s and gained momentum in the early 1990s. It is proposed for tropical and equatorial regions where seafloor bathymetry allows a reasonably short cold seawater intake pipeline (Syed et al. 1991). SWAC replaces chillers used in conventional AC systems, greatly reducing the electricity consumption and cooling costs (Makai Ocean Engineering 2015). The electricity cost of a SWAC system is usually 80% lower than conventional AC systems (Van Ryzin and Leraand 1991; Van Ryzin and Leraand 1992), and consists of around 20% of SWAC total project costs (Development Bank of Latin America 2015). These cooling demand projects should be as large as possible with the intention of reducing the overall costs of the project due to economies of scale (Development Bank of Latin America 2015). This is further explained throughout the paper.

Possible customers with high cooling demands to connect to district cooling systems are airports (González and Wabitsch 2017; Davidson 2003), data centers (Zhang et al. 2014; Koronen et al. 2019), hotels (International Renewable Energy Agency 2014c), resorts (International Renewable Energy Agency 2014a, c), governmental and military facilities, universities (Ocean Thermal Energy Corporation 2015), large offices and commercial buildings (International Renewable Energy Agency 2016; International Renewable Energy Agency 2017b), shopping malls (Li et al. 2007; Yik et al. 2001), department stores (Song et al. 2007), museums (Museu do Amanhã, 06 n.d.), residential districts, industrial processes (Ocean Thermal Energy Corporation 2015), entertainment facilities (Porak et al. 2013) (artificial ski resorts (Kim et al. 2012; Lee et al. 2014)), temperate fruits and vegetables farming, food and grains storage (von Herzen et al. 2017), and so on. SWAC also contributes to reduce heat islands due to air-conditioning (Shickman and Rogers 2019). A detailed worldwide cost estimate for SWAC can be seen in (Hunt et al. 2019). Bearing in mind the expected demand growth for cooling from a SWAC project, this paper suggests a modification to the normal design that can increase efficiency of SWAC projects with long pipelines as well as allow for expansion to meet growing cooling demand. The proposal consists of increasing the excavation depth of the seawater pump station, which allows an increase in the velocity and flowrate of the seawater inlet pipeline. We call this approach "High Velocity SWAC." This design configuration allows SWAC projects to be built with an initial cooling load and expand the cooling load modularly by smaller additional capital costs. Additionally, this paper explores the synergy between SWAC projects with thermal energy storage and renewable energy sources of electricity. The excess generation of electricity from variable renewable energy (VRE) sources, namely wind and solar energy, can be balanced out with the variations in seawater flow in the pipeline of SWAC plants. This cold water would then be stored in thermal energy storage tanks to meet the cooling demand at any time.

This paper is divided into five main sections. "Conventional SWAC plants" presents the conventional SWAC process providing details of the system components. "Methodology: High velocity SWAC with thermal energy storage" presents proposed changes in the design of SWAC plants through the high velocity SWAC proposal.

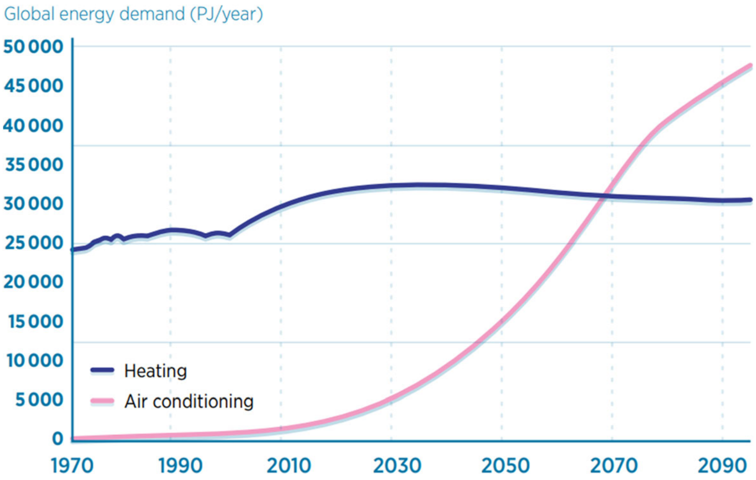


Fig. 1 Projected global demand for heating versus cooling, 1970–2090 (Isaac and van Vuuren 2009)

This section discusses more details on the required changes in the seawater pump station to reduce cavitation, thermal energy storage tanks and synergies with balancing of VRE. "Results" presents a cost analysis of conventional SWAC plants and compares it with high velocity SWAC plants. It also presents scenarios in which high velocity SWAC would operate with and without VRE. "Discussion" concludes the paper.

Conventional SWAC plants

Figure 3a and b presents the basic configuration of a conventional SWAC system. It is divided in five main parts: (1) the seawater inlet is the pipeline used to transport the seawater to the coast; (2) the seawater pump delivers the water from the ocean into the heat exchanger and them back to the ocean; (3) the seawater outlet is the pipeline used to return the seawater back to the ocean; (4) the heat exchanger or chilled water production plant is used to exchange heat from the seawater and district cooling or heating system; (5) the distribution network distributes the cold fresh water from the SWAC plant to the customer substations (Hernández-Romero et al. 2018). This section presents details on the components with are not altered in the new proposed SWAC design. For more details, refer to Development Bank of Latin America 2015; Elsafty and Saeid 2009; International Renewable Energy Agency 2014a, c.

Deep seawater inlet

The cold seawater inlet consists of a pipeline and tunnel connecting the ocean at around 700 to 2000 m depth

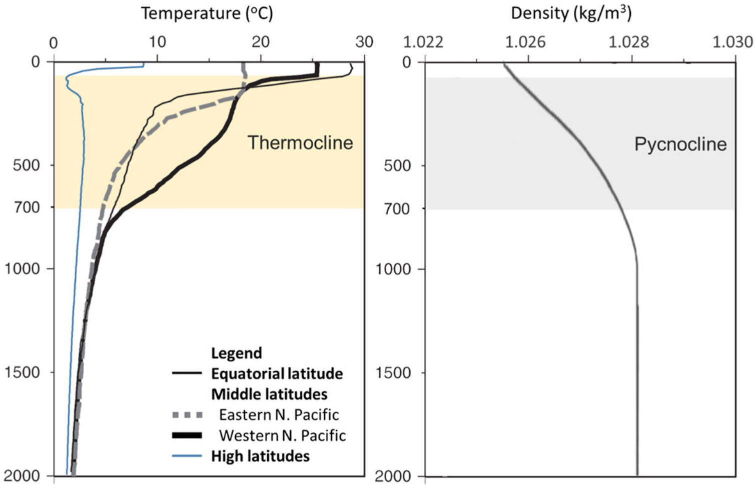


Fig. 2 Typical temperature and density variation with water depth in the open ocean. Adapted from (Satellite Applications for Geoscience Education 2017; Talley et al. 2011)

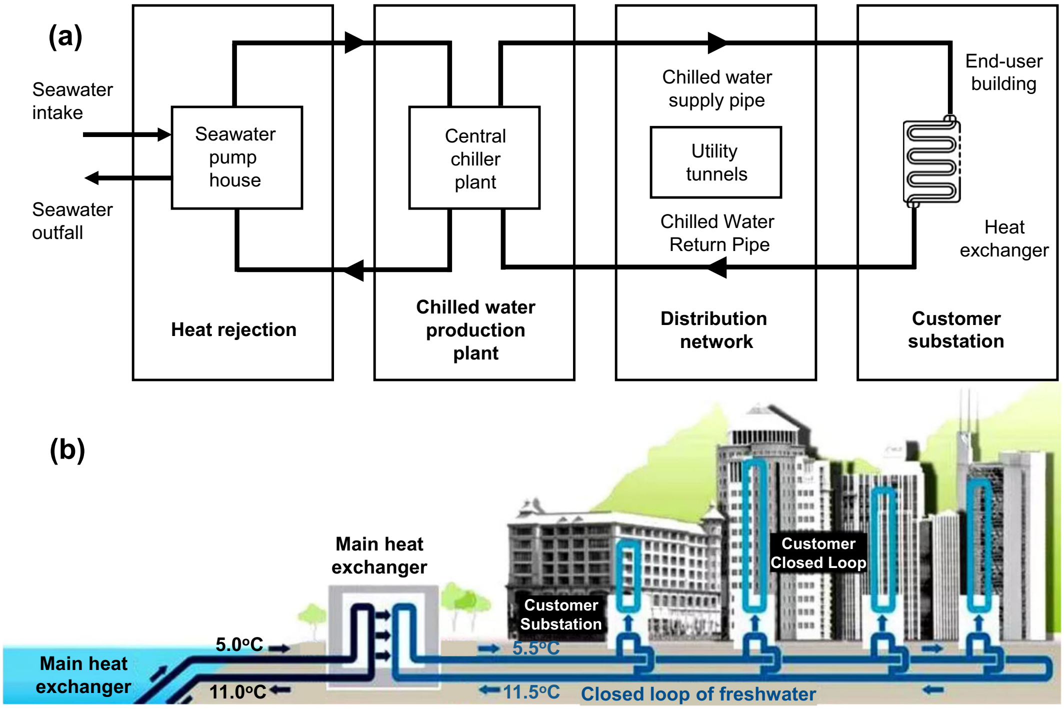


Fig. 3 Seawater air-conditioning **a** process diagram and **b** longitudinal section (Chow et al. 2004; Ecosis 2015)

with a heat exchanger at the coast. The length of the pipe can vary from 1 to 20 km. The longer the inlet pipeline, the higher its capital costs, electricity load for pumping, and energy losses to the surroundings.

Although cost of pipeline is proportional to the square of pipeline diameter, large pipes are more interesting than a collection of small pipes, as their friction and heat exchange are also smaller and an increase in diameter increases the cooling load to the square. Additionally, the installation costs and maintenance costs of the pipeline do not vary considerably with changes in diameter of the pipeline.

The inlet pipeline usually consists of high-density polyethylene (HDPE), which has several advantages over alternative materials (strength, durability, flexibility, inertly, insulation, resistance to high pressure, cost effectiveness, and slight negative buoyancy). During construction, the pipeline is filled with air and towed into place and lowered to the seabed (Lewis et al. 1988). The HDPE pipeline is ballasted using a variety of concrete weight designs, most commonly a variation of concrete anchor clamped tight around the HDPE pipeline (Development Bank of Latin America 2015). The flexibility of the pipeline is a critical issue, as it may suffer stress from marine currents, seismic activities as well as expansion and contractions from temperature changes (especially in the surface layer of the ocean) (Lewis et al. 1988). HDPE pipes also require less insulation because the plastic is inherently less conductive than metal. A study of possible materials and designs for the deep seawater pipeline can be seen in (Miller et al. 2012). Lewis et al. proposes different approaches for installing the pipeline on the seabed (Lewis et al. 1988).

Warm seawater outlet

The warm seawater outlet should return the deep seawater at around half of the length of the inlet pipeline or at depths of at least 50 m (Development Bank of Latin America 2015). This is to reduce the impact of the colder, saltier water on the marine environment. De Profundis prescribes an output at a minimum of about 200 m to avoid algae bloom. Environmental studies of the coastal areas of Hawaii (Mamala Bay, Ohanu and Hononlulu SWAC projects) have been developed to provide an understanding of pre-impact conditions at the future SWAC site and enable a more accurate environmental assessment (Comfort et al. 2015; Cardno TEC, 2014). An alternative use of the warmer seawater outlet, which can be rich in nutrients, is for the production of algae, fish, and crustaceans in controlled tanks or in the open ocean (International Renewable Energy Agency 2014b; Asian Development Bank 2014; von Herzen et al. 2017).

Heat exchanger

The heat exchanger allows the cold seawater to cool the re-circulating fresh chill-water loop used for air-conditioning applications. In a typical SWAC system, the cold seawater is pumped at 5 °C, arrives at 7–8 °C in the heat exchanger, goes through the heat exchanger, and leaves at 12–13 °C, as shown in Fig. 4. The fresh water of the air-conditioning system arrives at 13 °C and leaving at 8 °C, as shown in (International Renewable Energy Agency 2014c; Development Bank of Latin America 2015). Titanium heat exchangers are commonly used, since they combine corrosion resistance in salty water with high thermal conductivity (Elsafty and Saeid 2009; Makai Ocean Engineering 2014). Long-term testing of heat exchangers is reported to have demonstrated that fouling is not a serious problem with deep seawater (Makai Ocean Engineering 2014). Once the seawater passes through the heat exchanger, it is returned to the ocean through the warm seawater outlet.

District cooling

District cooling is the means used to distribute the cooling load from the SWAC plant to the cooling demand. District cooling is usually less viable than district heating systems. This is because steam is a better energy vector than water and the supply-and-return temperature differential of water in heating systems is usually much higher than for cooling systems. This results in larger pipe diameters and larger electricity consumption in district cooling pumping systems than in district heating systems. However, given that the costs of cooling with SWAC processes can be quite low, district cooling over short distances becomes a viable alternative. Sometimes the costs of district cooling are higher than the costs of the SWAC project. This can happen where the cooling demand is highly fragmented, for example, in the case study in Montego Bay, Jamaica, as shown in "Seawater pump." Details of existing district cooling case studies, district cooling implementation in countries, the potential for district cooling up to 2030 and the barriers and opportunities of district cooling see (International Renewable Energy Agency 2017a). Challenges and solutions in the optimization and implementation of district cooling can be seen in (Asim et al. 2019). Retrofit costs for conventional AC systems into district cooling alternatives are shown in (Development Bank of Latin America 2015; Dominković and Krajačić 2019; Levinson and Akbari 2010). More details on radiant cooling systems can be seen in Hu and Niu 2017.

Methodology: high velocity SWAC with thermal energy storage

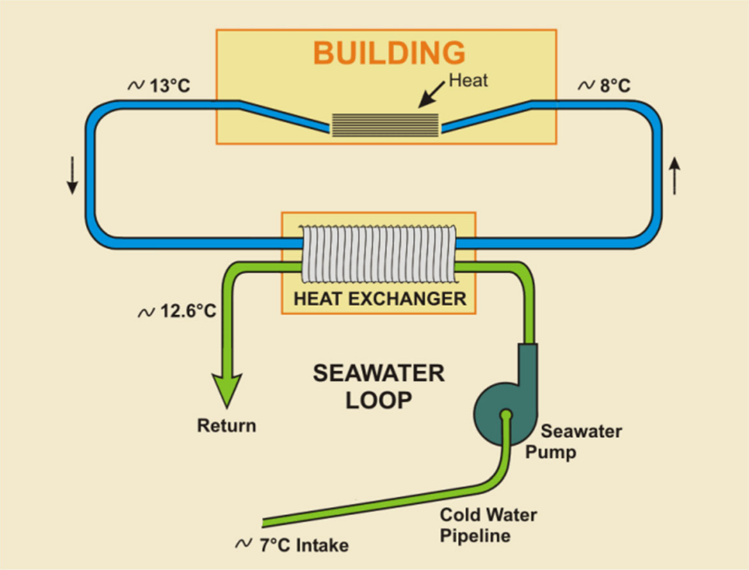
This section proposes design changes to the conventional SWAC plant. Figure 5 presents the configuration of the high velocity SWAC system suggested in this article, which includes the combination of high depth pump station excavation and thermal energy storage. The proposed SWAC system requires seven main parts; these are (1) cold seawater inlet; (2) warm seawater outlet; (3) seawater pump, which is excavated at a reasonable depth to allow a future increase in flowrate without cavitation; (4) heat exchanger; (5) thermal energy storage tank; (6) refrigeration systems or district cooling system; and (7) renewable sources of energy. The parts with substantial design contributions are proposed in the following sections.

The high velocity SWAC terminology was used to indicate that the flowrate of the SWAC system can be increased without the need for building new seawater inlet and outlet pipelines, which have a large capital cost. Instead, the velocity of the seawater can be increased to enhance the flowrate and, thus, increase the cooling load of the SWAC system. However, to allow for the upgrade of the system, the seawater pump must be excavated to prevent that cavitation happens with the increase in velocity of the flow in the pipeline. Cavitation is a common issue in SWAC plants and even closed loop systems have been proposed to reduce the impacts of cavitation (Guarino and Garnier 2019). The following section presents the changes in design of the seawater pump to allow for an increase in cooling load in the SWAC plant and avoid cavitation.

Seawater pump

The seawater pump station is typically designed using either a wet or dry sump onshore near the

Fig. 4 Diagram of a SWAC system heat exchanger (Development Bank of Latin America 2015)



coast and must be installed deep enough to account for the total head loss in the offshore intake pipe (Development Bank of Latin America 2015). Thus, usually the deep seawater inlet pipeline and the seawater pumping station are excavated up to 2 to 5 m from sea level. This is due to two factors, which are presented in Eqs. 1 and 2. Firstly, the seawater in the pipeline, during operation has a constant salinity equivalent to the seawater depth in which it is extracted. This density is higher than the average density profile up to a depth in which the seawater is extracted. Figure 2 presents the typical density gradient at the world's oceans with depth. The minimum head required for the seawater to reach the pump can be calculated with Eq. 1. Assuming the change in density with depth from Fig. 2, Eq. 1, and depths of 700 and 1400 m, the head difference between the sea level and the seawater pump station

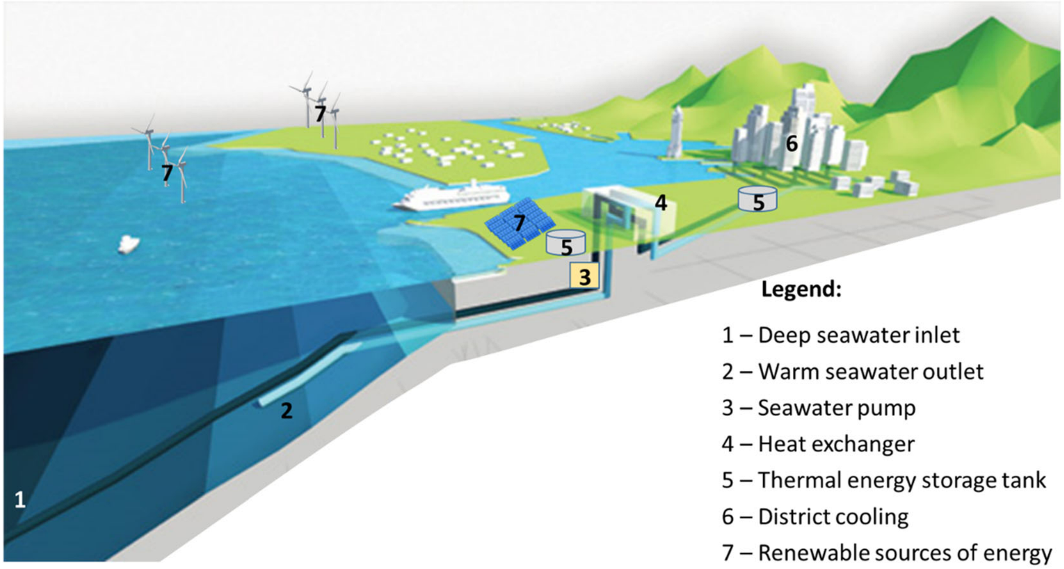


Fig. 5 Deep seawater air-conditioning scheme main parts. Adapted from (Honolulu Seawater Air Conditioning 2017)

level (H) is equal to 0.82 and 1.2 m.

$$H = (\rho_d - \rho_{\text{av}}) \times D \tag{1}$$

where:

- H is the head loss due to the density difference between the ocean and the inlet pipeline (m), which equals to 0.82 m for a depth of 700 m and 1.2 m for a depth of 1400 m.
- ρ_d is the density of seawater at a depth "D" of 1.02755 kg/l for a depth of 700 m and 1.02800 kg/l for a depth of 1400 m.
- ρ_{av} is the average density of seawater from the surface until depth "D" of 1.02638 kg/l for a depth of 700 m and 1.02711 for a depth of 1400 m.
- D is the depth of the SWAC pipeline inlet in meters.

The second factor that contributes to the seawater pump excavation depth is the head loss due to the flow in the pipeline during the operation of the SWAC system. The main aspect that influence head loss is the friction in the pipeline. This can be calculated by Eq. 2 (The Engineering Toolbox 2018a).

$$\Delta h = \lambda \times \frac{l}{2g} \times \frac{v^2}{d} \tag{2}$$

where:

- Δh is the head loss due to friction in the seawater inlet and outlet, which is equal to 1.39 m assuming a velocity of 1 m/s and 5.56 m if the flow velocity increases to 2 m/s.
- λ is the Darcy friction factor, assumed to be 0.03 (The Engineering Toolbox 2018a).
- l is the length of the pipe or duct, assumed to be 1000 m.
- d is the diameter of the pipe, assumed to be 1.1 m.
- v is mean flow velocity, measured as the volumetric flow rate divided by the cross-session area of the pipe, assumed to be 1 m/s.

In order to start up the pump, fresh water should be added into the seawater inlet at the pump's end so that the level of the seawater inlet head can rise and reach the seawater pump station. Then, the pump will operate by sucking the seawater from the water pump inlet. Seawater at 7 °C (temperature at the pump during normal operation) has a vapor pressure of 0.00982 bar (The Engineering Toolbox 2018b); thus, the maximum theoretical head for suction would be around 10 m at this temperature. If the suction power increases above, this set value cavitation will happen, which would damage the pump and pipeline. In order to maintain a conservative suction head, this paper assumes a 2-m suction head.

The high velocity SWAC plants proposed in this paper are designed with high depth pump station excavation designs. With the increase in the seawater pump station depth, higher seawater velocities can be reached in the pipeline. An increase in velocity in the tubes is beneficial because it increases the cooling load, proportionally, and it reduces the water residence time in the pipeline, and could reduce heat loss to the surroundings. However, it might increase capital costs due to the increase in excavation needs of the seawater inlet tunnel and the seawater pump station and increases friction head loss, thus, increases electricity consumption. All these parameters need to be equated to find the most optimum and cost effective SWAC plant design.

An example of a high velocity SWAC project has been developed using the similar design parameters as in the SWAC project in Puerto Plata (Development Bank of Latin America 2015). The main differences in design were the increase in seawater inlet pipeline diameter to 1.3 m and increase the excavation depth below sea level. This allows a considerable increase in cooling load in the future. Table 1 presents the changes in total head loss with the seawater inlet pipeline with changes in the seawater flowrate. As it can be seen, according to Eq. 2, the friction head loss varies with the square of the speed and mass flow. For the case study developed in this section, the selected mass flow and velocity in the seawater inlet is set to the vary from 761 kg/s and 0.56 m/s during the initial years of operation of the SWAC plant and increase two times to 1521 kg/s and 1.12 m/s, doubling the cooling load. Note that the electricity consumption in the seawater inlet in Table 1 is much lower than the electricity consumption in conventional AC systems with a COP of 3 to 4. The excavation depth increases exponentially with the further increase in mass flow. In order to achieve a reasonable velocity variation, the seawater inlet and seawater pump station is designed 14.1 m below sea level for doubling the cooling load. A schematic diagram presenting the upgrades to the system are presented in Fig. 6.

The payback of the different flowrate cannot be compared because, with the given demand, the initial design is the most viable option. The upgraded plant is only considered if the cooling demand

Table 1 Sensitivity of excavation depth and electricity consumption to seawater inlet mass flow

Parameters	Initial design	Upgrade mass flow (× 2)
SWAC project characteristics		
Inlet plus outlet pipeline lengths (m)	10,200	10,200
Diameter (m)	1.3	1.3
Mass flow (kg/s)	761	1522
Volumetric flow (m^3/s)	0.74	1.48
Inlet pipeline velocity (m/s)	0.56	1.12
Cooling load		
Cooling load with mass flow (MW_t)	15.6	31.2
Head loss		
Friction head loss (m)	3.7	14.9
Density head loss (m)	1.2	1.2
Total head loss (m)	4.9	16.1
Suction head (m)	2.0	2.0
Pump station excavation depth (m)	2.9	14.1
Electricity requirements for the SWAC system		
Freshwater pump elect. cons. (MW_e)	0.33	0.66
Seawater pump elect. cons. (MW_e)	0.05	0.30
Total electricity consumption (MW_e)	0.38	0.96
COP	41.5	32.5

increases after the initial design has been already built, as it might make more sense to upgrade the existing SWAC plant, then to build a new one.

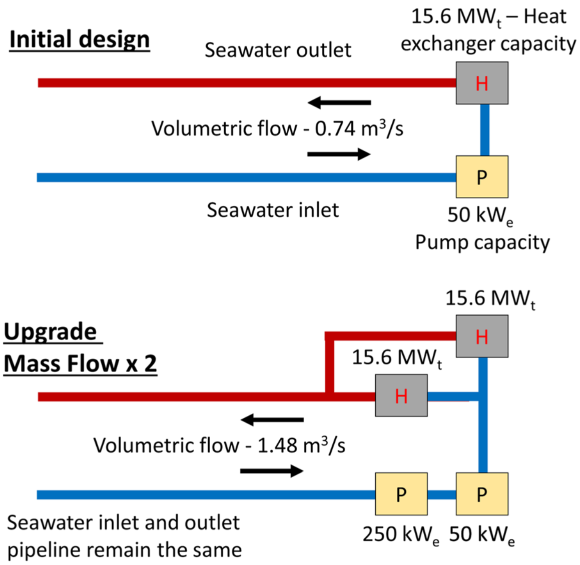


Fig. 6 Diagram of the upgrade of the initial SWAC system due to the increase in cooling demand

Thermal energy storage tanks

There are two approached for thermal energy storage in SWAC projects, to store the cold seawater extracted from the deep seawater in tanks for daily or weekly storage cycles, or to freeze freshwater for monthly or seasonal energy storage (Development Bank of Latin America 2015).

Cooling demand seawater for daily storage

As SWAC projects have high capital costs, the pipes, pumps, and heat exchanger should operate with high load factors to justify the investment in the technology, assuming that electricity prices are constant. However, the demand for cooling services might vary considerably in daily cycles; it is usually lower or non-existent during the nighttime and high during the day, peaking during the afternoon. Daily thermal energy storage is important to allow the seawater inlet pipes, the pumps, and the heat exchanger of the SWAC system to operate constantly and guarantee the cooling demand during different hours of the day. During periods of low cooling load (i.e., at night), the thermal energy storage tank is filled with cold seawater. During the day, the stored chilled seawater is used to lower the temperature of the district cooling system (Development Bank of Latin America 2015). A demonstration of the daily seawater energy storage tank operation is presented in Fig. 7.

Equation 3 presents the implementation of thermal energy storage in SWAC systems. Equation 4 presents the balance of thermal energy storage within the tanks.

$$C = L + T_{\mathrm{in}} - T_{\mathrm{out}} \tag{3}$$

where:

C is the cooling demand (MW_t).
L is the cooling load (MW_t).
T_{in} is the amount of cooling thermal energy added to the thermal energy tank (MW_t).
T_{out} is the amount of cooling thermal energy extracted from the thermal energy tank (MW_t).

$$\mathrm{TES}_i = T_0 + T_{\mathrm{in}} - T_{\mathrm{out}} - \mathrm{Loss} \tag{4}$$

where:

TES_i is the amount of thermal energy available in the storage tank at the time i in (MWh_t).
T_0 is the initial charge in the thermal energy storage tank (MWh_t).

Loss is the amount of cooling potential loss to the surroundings, increasing the temperature of the seawater in the tank (MWh_t). The assumed energy loss for a daily energy storage cycle is 95%.

Intermittent renewable energy seawater storage

As mentioned in "Deep seawater inlet," the increase in seawater pumping station depth allows more head loss in the system and thus an increase in deep seawater speed in the seawater inlet pipeline. The increase in speed and head loss in the pipeline results in an increase in electricity consumption. Given that the electricity prices might vary in accordance with the availability of wind and solar generation sources and during peak and off-peak periods, the amount of electricity used for pumping can vary with electricity costs. Similarly to the section above, when electricity costs are low and the cold seawater pumped provides more cooling load than the demand, some of the water is stored. When electricity costs are high and the seawater pumped provides less cooling load than the demand, the stored water is used to complement the remaining cooling demand. This mechanism is further detailed in the "Results" section.

Seasonal thermal energy storage

If the demand for cooling is seasonal, a large freshwater tank can be used to store thermal energy by freezing the water. During the months where cooling is not required, the cold seawater from the SWAC plant is used to increase the efficiency of a chiller to freeze freshwater in a tank. During the months when cooling demand is high, both the SWAC system and the energy stored as ice in the freshwater tank are used to supply the cooling demand.

Synergies between variable renewable sources and SWAC

Currently, the electricity generation sector is going through fundamental changes with the intention of reducing CO_2 emissions and fossil fuel dependence with renewable sources of energy such as wind and solar gaining market penetration. However, the electricity generated from these sources can be intermittent, difficult to predict and not match the timing of the demand. Thus, energy storage is an important aspect to allow the intermittent and unpredictable renewable energy to meet

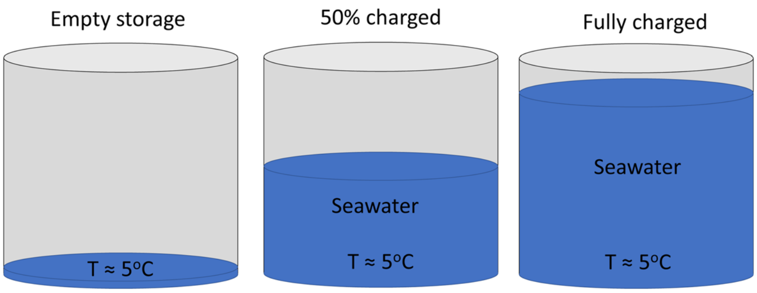


Fig. 7 Seawater thermal energy storage tank for daily or weekly energy storage

the demand for electricity and to increase the viability of these renewable energy sources.

Comparing pumped storage, the benchmark technology used for energy storage, with SWAC thermal energy storage systems, the latter has several advantages when considered for cooling services energy storage. A 10 °C temperature difference water volume stores the same amount of energy as a pumped storage plant with 2092 m (assuming an efficiency of 80% and a refrigerant with a 2.5 COP). A pumped storage plant requires two reservoirs (upper and lower); a tunnel connecting both reservoirs; a power station with a turbine, generator, and auxiliary equipment; a transmission line connecting the pumped storage plant and the cooling demand; and a refrigeration system to turn electricity into cooling. The usual capital costs of pumped storage projects are in the range of \$2000/kW$_e$ installed (Akinyele and Rayudu 2014), i.e., \$800/kWt installed (assuming a refrigerant with a 2.5 COP). Due to gains in scale pumped storage tends to be viable with 100 MW$_e$ capacity or higher.

The pump is the only electrical component of a SWAC system (International Renewable Energy Agency 2014c). Storing the cold water pumped during moments of excess renewable electricity generation is equivalent to storing electricity in a grid operational perspective. If the SWAC project is built according to the suggestions in this paper, the thermal energy storage systems would only require a cold seawater or freshwater reservoir. The heat loss in the thermal energy storage system is 0.5 °C (Development Bank of Latin America 2015), which makes the system ~ 95% efficient, assuming that a 10 °C temperature difference of the stored cold water is used in the cooling process. The capital cost of SWAC thermal energy storage is estimated to be \$585/kWt (Development Bank of Latin America 2015), substantially smaller than the costs of the pumped storage system presented above. In addition, thermal energy storage systems are viable with cooling demands as low as 20 MW$_t$ (Development Bank of Latin America 2015). More details on the comparison of thermal energy storage with other energy storage technologies can be seen in (Smallbone et al. 2017).

In addition, a SWAC project with thermal energy storage tanks and a district cooling system could be enhanced with a heat pump that consumes electricity during periods when electricity prices are low to freezes some of the fresh water in a seasonal thermal energy storage tank (Abdullah et al. 2013). This would considerably increase the energy storage capacity of the thermal storage tank and increase the synergies for optimizing VRE systems. SWAC processes with thermal energy storage will have an important role in supporting the dissemination of VRE in the coming years in regions where SWAC is a viable alternative for cooling.

Results

The "Results" section is divided into two subsections. One focus on the economic analysis of high velocity SWAC designs and the costs for expanding the cooling load capacity after the SWAC project has already been built with a deep seawater pump station. The other section focuses on presenting an example of operation of high velocity plant SWAC with thermal storage in synergy with the generation of VRE.

Economic analysis of high velocity SWAC design

The main aspects that influence the cost of SWAC systems are the distance from the coast to ocean depths were the seawater temperature is 5 °C or less (the lower the distance the better), the depth required to reach this temperature, which varies from 700 to 2000 m (the lower the depth the better), the demand for cooling (the higher the demand the better), district cooling system (the less defragmented the better) costs, and electricity costs (the higher the better). A detailed cost analysis has been performed in (Development Bank of Latin America 2015) taking into account all these variables. Another important aspect, due to the high capital costs, is the interest rate on borrowed capital, which is assumed to be 11.5% in this study. The estimated capital costs and operation cost for SWAC and conventional AC systems in Montego Bay, Jamaica and Puerto Plata, Dominican Republic are presented in Fig. 8 (Development Bank of Latin America 2015). The design values are presented in Table 2 were taken from (Development Bank of Latin America 2015). The heat exchanger cost is assumed to be part of the distribution cost in (Development Bank of Latin America 2015), and its cost estimate was taken from (Elsafty and Saeid 2009).

The average investment required for SWAC systems is about USD\$ 4000/kW of air-conditioning load and the average levelized cost of thermal energy is USD 0.055/kWh, and the payback period is between 5 and 11 years (International Renewable Energy Agency 2014c). However, these costs considerably reduce with the increase in cooling demand. The design suggested presented in this

Table 2 SWAC project parameters in Montego Bay and Puerto Plata (Development Bank of Latin America 2015)

Parameters	Montego Bay	Puerto Plata
Technical summary		
Peak AC load (MW_t)	27.0	24.0
Average AC load (MW_t)	16.6	15.6
Intake pipe		
Depth of intake (m)	− 917	− 1082
Length of intake pipe (km)	4.6	8.0
Outside diameter of intake pipe (m)	1.10	1.10
Seawater velocity (m/s)	0.86	0.79
Head loss due to friction in the pipe (m)	3.0	4.4
Head loss due to density difference (m)	11.1	11.8
Deep water temperature (°C)	5.77	5.81
Return pipe		
Depth of return pipe (m)	− 50	− 50
Length of return pipe (km)	1.1	2.2
Outside diameter of return pipe (m)	1.00	0.80
Max. temperature of returned water (°C)	12.3	12.5
Seawater pump station		
Mass flow (kg/s)	844	761
Seawater pumping power (MW_e)	0.17	0.20
Excavation depth (m)	− 2.2	− 3.1
Chilled water pump station		
Total flow (kg/s)	844	724
Freshwater pumping power (MW_e)	0.637	0.33
COP of the SWAC system	20.6	29.4
Heat exchangers		
Seawater ΔT across heat exchanger (°C)	6.07	5.80
Seawater flow (kg/s)	844	761
Fresh water flow (kg/s)	804	724
Thermal energy storage		
Thermal energy storage peak flow (kg/s)	-	298.98
Thermal energy storage tank capacity (Ml)	11	11
Energy loss with storage (°C)	0.5	0.5
Financial parameters		
Interest rate (%)	11.5	11.5
Electricity costs ($/kWh)	0.36	0.32

article could be used to increase the cooling demand of SWAC systems and, thus, increase its viability. An analysis of different cooling alternatives for tourist islands is presented in (International Renewable Energy Agency 2014c).

In the SWAC design proposed in this paper, the inlet pipeline will be constructed similarly as a conventional project. This is with a velocity in the tunnel of around 0.5 m/s with the intent of reducing the head loss in the pipeline and reduces electric consumption. The speed of the seawater in the pipeline is planned to increase in the future with the increase in cooling load and the costs of the inlet and outlet pipeline remains constant.

In order to analyze the costs of additional cooling demand with the increase in water flow velocity in the inlet and outlet pipelines, this work has divided the costs

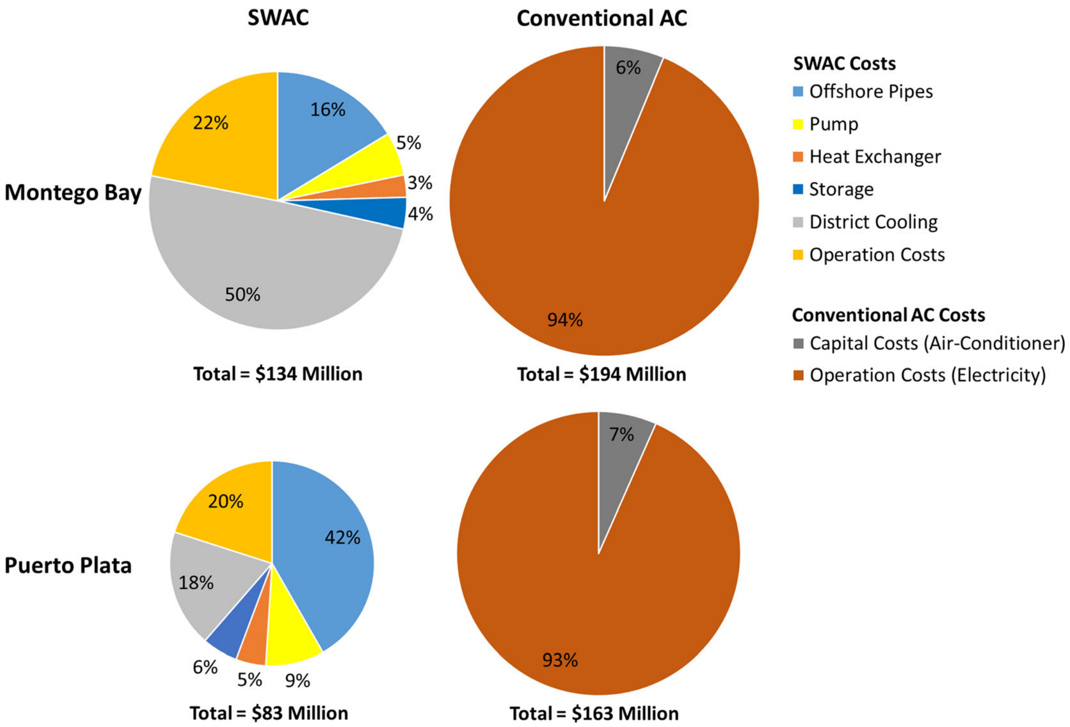


Fig. 8 Cost estimation of SWAC and conventional AC in Montego Bay and Puerto Plata (Development Bank of Latin America 2015)

of the project in initial cost and project costs. The initial cost varies with changes in inlet and outlet seawater pipelines (offshore pipelines), pump station, heat exchanger, thermal storage, and distribution network. The project costs include the operation costs, which is equivalent to the electricity costs for pumping. In the proposed design for high velocity SWAC, the increase in cooling demand requires a similar investment in pump station, heat exchanger, thermal storage, and distribution network. However, there is no need for new investment in the offshore pipelines.

Given that the inlet and outlet pipelines were designed with an initial low velocity and a larger excavation depth to allow the pump to increase the velocity in the inlet pipeline, the increase in cooling load will not require additional investments in the inlet and outlet pipelines. Applying Eqs. 1 and 2, similarly to Table 1, using the same cost estimates as in Fig. 8 for the Puerto Plata SWAC project, the additional costs for expanding the SWAC cooling load are related to the component costs presented in Table 3. This estimate assumes that the freshwater pump electricity consumption increases proportionally to the increase in cooling demand. The pump station excavation cost for the initial design is estimated to be 500,000$ for a 2.9-m excavation. The cost of excavation for the first upgrade is for estimated as 5000,000$ for a 14.1-m excavation (Slapgard 2012).

As it can be seen in Table 3, the initial costs of doubling the cooling load of the existing SWAC project are only 55% of the initial costs. The increase in velocity in the pipeline, however, increases the electricity consumption of the project in 152%, which results in a final total cost for the expansion in cooling load of 83%. Doubling the cooling load results in a final cost of 83% of the initial cost and should be considered in the initial design of the plant. The analysis in Table 3 assumes constant electricity price. In a scenario where electricity prices vary with the availability of wind or solar energy, the seawater pump electricity consumption can vary with the price of electricity, further increasing the advantage of increasing the pumping capacity of the system. The next subsection reproduces the operation of the high velocity SWAC plant together with thermal storage.

Integration of thermal storage in high velocity SWAC plants

Applying the design parameters in Table 1, two operational scenarios present the benefits of building the seawater pump stations with higher excavation depths.

Table 3 Additional costs for extension of the cooling load with the same offshore pipeline for the Puerto Plata SWAC project (Development Bank of Latin America 2015)

Component costs	Initial design cost (1000 $)	Upgrade 1 cooling load × 2 cost (1000 $)	Upgrade 1 cost increase from initial project to cooling load × 2
Capital cost			
Offshore pipeline	34,725	0	0%
Pump station	7688	7687	100%
Heat exchanger	3931	3.93	100%
Thermal storage	4707	4707	100%
Distribution	15,461	15,461	100%
PS excavation	500	5000	1000%
Capital cost	67,012	36,787	55%
Overall project cost			
Capital cost	67,012	36,787	55%
Electricity	11,136	28,134	152%
Total costs	78,148	64,921	83%

The first operational scenario uses the initial design assuming the cooling demand from Chow et al. (2004) and the SWAC project proposed in Puerto Plata, with energy storage. The second operational scenario assumes a twofold increase in cooling load, electricity supplied with solar and wind energy, and some of the energy is stored with thermal energy storage.

Figure 9 presents the designed operation for the of a new SWAC project. It assumes that a seawater thermal energy storage is implemented with the intention of keeping the plant's seawater inlet and pump station operating at maximum capacity to justify the investment costs. The seawater thermal energy storage capacity required is 125 MWh. This design allows all cooling demand to be provided by the SWAC plant. The SWAC plant operates at maximum capacity throughout the day and night, and the thermal storage tank is filled during the night and consumed during the day.

Figure 10 presents the second operation scenario with a twofold increase in cooling load. Now energy is stored when the solar and wind energy is higher than the demand (especially during early morning hours) and the stored thermal energy is consumed when the demand is higher than the renewable energy supply (especially during the late

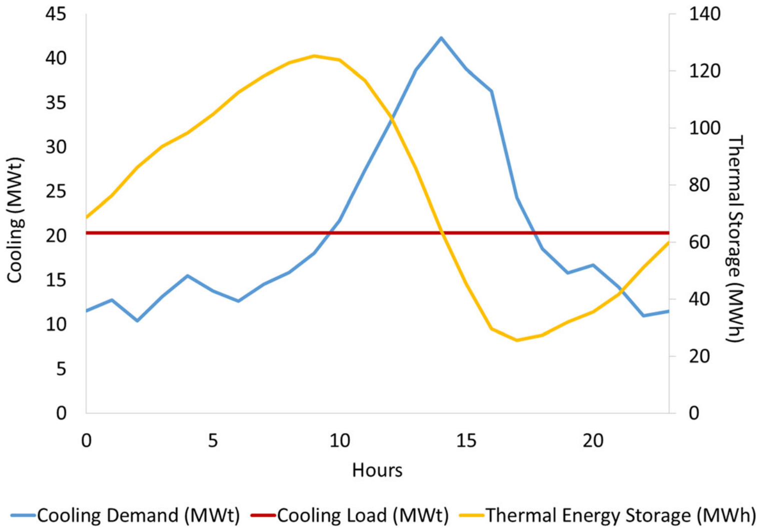


Fig. 9 Operation scenario with initial design parameters

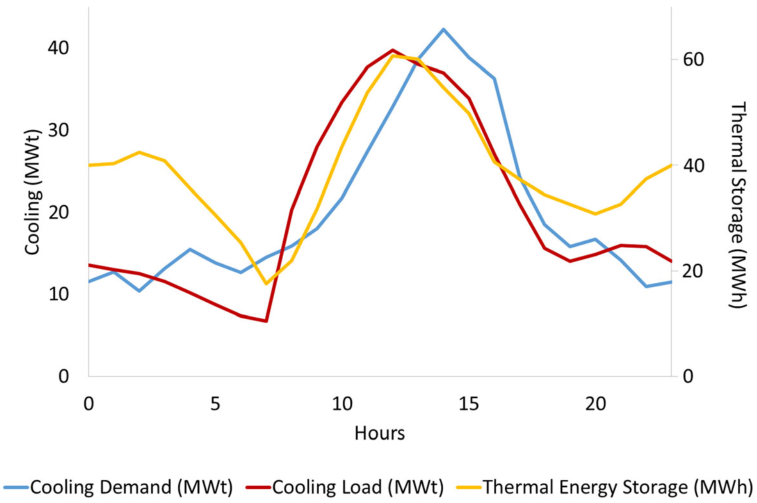


Fig. 10 Operation scenario with a twofold increase in cooling load and electricity supplied by a mixture of solar and wind energy

afternoon). It assumes that all electricity consumed in the cooling system comes from a mixture of solar and wind power. The solar generation estimates in Puerto Plata were taken from (Renewables Ninja 2017). This design allows the cooling demand to vary considerably with the availability of cheap electricity from wind and solar; the thermal storage tanks store energy when there is more renewable generation than cooling demand and consumes the stored heat when there is less renewable generation then the cooling load. This operation only makes sense if there is excess of VRE in the grid, which requires energy storage.

Discussion

Currently, there is a substantial movement to a transition to a hydrogen-based economy. Japan, Europe, and China already have ambitions plans for leaving the fossil fuel industry and use hydrogen instead. This increase in demand in hydrogen will motivate countries with high renewable energy potential to export their potential in the form of H_2. One of the options to transport hydrogen is liquifying it. One very good opportunity for the development of SWAC projects in the future is to reduce the energy requirements for the liquefaction of hydrogen by the coast, or in oceanic platforms. Depending on the climate of the location, SWAC could reduce the energy consumption for liquefaction in 10 to 15%.

Conclusions

This paper demonstrates that the seawater pump station in SWAC projects should be designed with an excavation depth up to 20 m below the sea level, instead of the common 2–5 m. This design consideration allows the velocity of the seawater in the offshore pipelines to increase twofold, which would result in a similar increase in the provided cooling load. The increase in seawater velocity and cooling load would require addition pumps, heat exchangers, and distribution network; however, the offshore pipeline will remain the same. Estimates show that the capital cost for doubling the cooling load is equivalent to 55% of the initial capital cost and 83% of the overall cost of cooling.

An increase in the excavation depth is especially beneficial if the inlet seawater pipeline is long (10 to 20 km). Due to the larger share of the offshore pipeline cost in the overall project, the enhanced utilization of the pipeline can be achieved in higher seawater velocities. Higher seawater velocity will result in a lower residence time of the seawater in the pipeline, thus, smaller overall heat losses. In addition, with a higher excavation depth, centrifugal pumps can be applied, which can further reduce the capital costs of the project compared to the existing configurations.

The proposed design configuration allows SWAC projects to be built with an initial cooling load that guarantees the contracted cooling demand for customers that are willing to invest in the technology. Given the challenges and high risks for building SWAC projects, after the SWAC project is built the cooling demand could increase considerably due to additional customers that were firstly reluctant using the technology. Additionally, given the low cost of cooling services provided by the available SWAC project, the location might have an increase in high cooling demand customers, for example, a hotel resort, which can utilize an expanded version of the SWAC plant. This allows the project developer to design the project with a small cooling load and implement modular extensions in the cooling load, which reduces the project implementation costs and risks.

Synergies between VRE, such as solar and wind, and SWAC with thermal energy storage are particularly worthy of further analysis. This is because the operation of SWAC plants could vary according to the availability of solar and wind generation as a demand-side management alternative to reduce the impact of intermittence in the grid. Thus, SWAC processes with thermal energy storage will have an important role in supporting the integration of VRE in regions where SWAC is a viable alternative for district cooling and the share of VRE is high in the grid.

Funding Open access funding provided by International Institute for Applied Systems Analysis (IIASA). We would like to thank the National Agency of Petroleum, Natural Gas and Biofuels (ANP), the Financier of Studies and Projects (FINEP) and the Ministry of Science, Technology and Innovation (MCTI) through the Human Resources Program of the ANP for the Oil and Gas Sector Gas–PRH-ANP/MCTI, in particular PRH-ANP 53.1 UFES, for the financial support.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Abdullah, M., Yii, L., Junaidi, E., & Tambi, G. (2013). Electricity cost saving comparison due to tariff change and ice thermal storage (ITS) usage based on a hybrid centrifugal-ITS system for buildings: a university district cooling perspective. *Energy and Buildings, 67*, 70–78.

Akinyele, D., & Rayudu, R. (2014). Review of energy storage technologies for sustainable power networks. *Sustainable Energy Technologies and Assessments, Volume, 8*, 74–91.

Asian Development Bank. (2014). *Wave energy conversion and ocean thermal energy conversion potential in developing member countries*. Manila: ADB.

Asim, M., et al. (2019). Thermo-economic and environmental analysis of integrating renewable energy sources in a district heating and cooling network. *Energy Efficiency.*

Cardno TEC, I. (2014). *Final environmental impact statement for the proposed Honolulu Seawater Air Conditioning Project, Honolulu, Hawaii*. Honolulu: US Army Corps Of Engineers.

Chow, T., et al. (2004). Energy modelling of district cooling system for new urban development. *Energy and Buildings, 36*, 1153–1162.

Comfort, C., et al. (2015). Environmental properties of coastal waters in Mamala Bay, Oahu, Hawaii, at the future site of a seawater air conditioning outfall. *Oceanography, 28*(2), 230–239.

Davidson, J. (2003). California;s energy future and cold ocean water. *Sea Technology, 44*(7), 30–34.

Development Bank of Latin America. (2015). *A pre-feasibility study for deep seawater air conditioning systems in the Caribbean*. Mexico City: CAF.

Dominković, D., & Krajačić, G. (2019). District cooling versus individual cooling in urban energy systems: the impact of district energy share in cities on the optimal storage sizing. *Energies, 12*(3), 407.

Ecosis. (2015). *Deep ocean water applications - sea water air conditioning.* [Online] Available at: https://www.ecosisltd.com/sea-water-air-conditioning. Accessed 13 Oct 2020.

Elsafty, A., & Saeid, L. (2009). Sea water air conditioning [SWAC]: a cost effective alternative. *International Journal of Engineering, 3*(3), 346–358.

González, J. & Wabitsch, V. (2017). *Harnessing marine resources for clean and secure islands revolve ,* s.l.: Revolve Media.

Guarino, A., & Garnier, B. (2019). *A closed loop see water air conditioning*. Paris: EasyChair.

Henley, J. (2015). *World set to use more energy for cooling than heating.* [Online] Available at: https://www.theguardian.com/environment/2015/oct/26/cold-economy-cop21-global-warming-carbon-emissions. Accessed 13 Oct 2020.

Hernández-Romero, I., et al. (2018). Cite as optimal design of air-conditioning systems using deep seawater. *Clean Technologies and Environmental Policy, 20*(3), 639–654.

Honolulu Seawater Air Conditioning. (2017). *Honolulu seawater air conditioning.* [Online] Available at: http://honoluluswac.com/. Accessed 13 Oct 2020.

Hu, R., & Niu, J. (2017). Operation dynamics of building with radiant cooling system based on Beijing weather. *Energy and Buildings, 151*, 344–357.

Hunt, J., Byers, E., & Sánchez, A. (2019). Technical potential and cost estimates for seawater air conditioning. *Energy, 166*, 979–988.

International Renewable Energy Agency. (2014a). *A path to prosperity: renewable energy for islands*. Abu Dhabi: IRENA.

International Renewable Energy Agency. (2014b). *Ocean thermal energy conversion: technology brief.* Bonn: IRENA.

International Renewable Energy Agency. (2014c). *Renewable energy opportunities for island tourism*. Abu Dhabi: IRENA.

International Renewable Energy Agency. (2016). *Renewable energy in cities*. Abu Dhabi: IRENA.

International Renewable Energy Agency. (2017a). *Renewable energy in district heating and cooling: a sector roadmap for remap*. Abu Dhabi: IRENA.

International Renewable Energy Agency. (2017b). *Renewable energy in district heating and cooling: case studies*. Abu Dhabi: IRENA.

Isaac, M., & van Vuuren, D. (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy, 37*, 507–521.

Jung, H., & Hwang, J. (2014). Feasibility study of a combined ocean thermal energy conversion method in South Korea. *Energy, 75*, 443–452.

Khosravi, A., Syri, S., Assad, M., & Malekan, M. (2019). Thermodynamic and economic analysis of a hybrid ocean thermal energy conversion/photovoltaic system with hydrogen-based energy storage system. *Energy, 172*, 304–319.

Kim, H. et al. (2012). *Feasibility study on the utilization of sea water resources for green Olympic blue ice rink.* Vladivostok, s.n.

Koronen, C., Åhman, M., & Nilsson, L. (2019). Data centres in future European energy systems—energy efficiency, integration and policy. *Energy Efficiency, pp.*, 1–16.

Lee, G. et al. (2014). *Sea water heat pump systems for ice rink energy saving.* Jeju Island, s.n.

Levinson, R., & Akbari, H. (2010). Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy Efficiency, 3*, 53–109.

Lewis, L., Ryzin, J. & Vega, L. (1988). *Steep slope seawater supply pipeline.* Torremolinos, s.n.

Li, Z., et al. (2007). District cooling and heating with seawater as heat source and sink in Dalian, China. *Renewable Energy, 32*(15), 2603–2616.

Makai Ocean Engineering. (2014). *SWAC: An introduction to seawater air conditioning*. Kailua: Makai Ocean Engineering, Inc..

Makai Ocean Engineering. (2015). *New renewable energy report released: seawater air conditioning in the Caribbean.* [Online] Available at: https://www.makai.com/makai-news/2015_07_24_new_renewable_energy_report_released/. Accessed 13 Oct 2020.

Miller, A., Rosario, T. & Ascari, M. (2012). *Selection and validation of a minimum-cost cold water pipe material, configuration, and fabrication method for ocean thermal energy conversion (OTEC) systems.* Baltimore, MD, s.n.

Museu do Amanhã, 06. (n.d.). *Sustentabilidade, pilar do Museu.* [Online] Available at: http://museudoamanha.org.br/pt-br/content/sustentabilidade-pilar-do-muse. Access date: 13 /10/2020.

National Oceanic and Atmospheric Administration. (2018). *World Ocean Atlas Climatology*. [Online] Available at: https://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl?parameter=t. Accessed 13 Oct 2020.

Ocean Thermal Energy Corporation. (2015). *Ocean thermal energy corporation: an introduction to ocean thermal energy conversion (OTEC) and seawater air conditioning (SWAC).* Pennsylvania: OTE.

Odum, H. (2000). Emergy evaluation of an OTEC electrical power system. *Energy, 25*, 389–393.

Porak, D., Van Zwieten, J., & Wiles, B. (2013). An analysis of Florida's sea water cooling resource. *Marine Technology Society Journal, 47*(4), 226–239.

Renewables Ninja. (2017). *Solar PV.* [Online] Available at: https://www.renewables.ninja/. Accessed 13 Oct 2020.

Satellite Applications for Geoscience Education. (2017). *Ocean waves: surface and interface waves.* [Online] Available at: https://cimss.ssec.wisc.edu/sage/oceanography/lesson4/concepts.html. Accessed 13 Oct 2020.

Semmari, H., Stitou, D., & Mauran, S. (2012). A novel Carnot-based cycle for ocean thermal energy conversion. *Energy, 43*, 361–375.

Shickman, K., & Rogers, M. (2019). Capturing the true value of trees, cool roofs, and other urban heat island mitigation strategies for utilities. *Energy Efficiency, 13*, 407–418.

Slapgard, P. (2012). *Cost base for hydropower plants: with a generating capacity of more than 10,000 kW*. Oslo: VEILEDER.

Smallbone, A., Jülch, V., Wardle, R., & Roskilly, A. (2017). Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. *Energy Conversion and Management, 152*, 221–228.

Song, Y., Akashi, Y., & Yee, J. (2007). Effects of utilizing seawater as a cooling source system in a commercial complex. *Energy and Buildings, 39*, 1080–1087.

Syed, M., Nihous, G. & Vega, L. (1991). *Use of cold seawater for air conditioning.* Honolulu, s.n.

Talley, L., Pickard, G., Emery, W., & Swift, J. (2011). *Descriptive physical oceanography: an introduction* (6th ed.). London: Elsevier.

The Engineering Toolbox. (2018a). *Darcy-Weisbach pressure and head loss equation.* [Online] Available at: https://www.engineeringtoolbox.com/darcy-weisbach-equation-d_646.html.

The Engineering Toolbox. (2018b). *Sea water properties.* [Online] Available at: https://www.engineeringtoolbox.com/sea-water-properties-d_840.html.

Van Ryzin, J. & Leraand, T. (1991). *Air conditioning with deep seawater: a reliable, cost effective technology.* Honolulu, s.n.

Van Ryzin, J., & Leraand, T. (1992). Air conditioning with deep seawater: a cost-effective alternative. *Sea Technology, 33*(9), 37–44.

von Herzen, B. et al. (2017). *A feasibility study of an integrated air conditioning, desalination and marine permaculture system in Oman.*. Muscat, s.n.

Yik, F., Burnett, J., & Prescott, I. (2001). Study on the energy performance of three schemes for widening application of water-cooled air-conditioning systems in Hong Kong. *Energy and Buildings, 33*(2), 167–182.

Zhang, T., Liu, X. H., Li, Z., Jiang, J., Tong, Z., & Jiang, Y. (2014). On-site measurement and performance optimization of the air-conditioning system for a datacenter in Beijing. *Energy and Buildings, 71*, 104–114.