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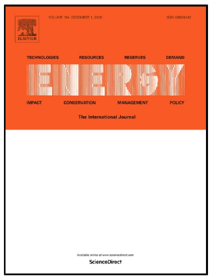

Technical potential and cost estimates for seawater air conditioning

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Energy

Technical potential and cost estimates for seawater air conditioning

Julian David Hunt[1], Edward Byers[2], Antonio Santos Sánchez[3]

In tropical climates, the energy consumed by ventilation and air conditioning can exceed 50% of the total consumption of a building. Demand for cooling is rising steadily, driven mainly by growing incomes in developing economies, and is expected to also increase with climate change. Tropical, coastal areas with narrow continental shelves are good sites for the implementation of Seawater Air Conditioning (SWAC), a renewable and low CO_2 emission cooling process. This paper presents the existing SWAC projects around the world and gives details on the technology. Data on ocean temperature profiles, ocean bathymetry and world surface temperature are processed with the intent of estimating the world potential of SWAC. The results present the required distance from coast to reach seawater with a temperature of 5°C or less. This is combined with the potential demand for air conditioning, taking into account surface air temperature and a set SWAC design for cooling from 30 to 20°C. The pipeline length, seawater depth and capacity factor are then used to estimate the costs of SWAC projects around the world. It is concluded that the locations with the highest potential for SWAC are intertropical islands and some continental locations.

Keywords: Building Refrigeration, Cooling, District Cooling, Energy Efficiency, Seawater Air Conditioning.

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Highlights

- This renewable source is ideal for tropical coastal areas with narrow continental shelves.
- The energy in a m^3/s of SWAC can be equivalent to 49 ha of solar PV or 42 MW of wind turbines.
- A novel SWAC potential model is developed to identify the most promising sites worldwide.
- Capacity factor, pipeline length, depth extraction and cost estimates are presented in detail.
- The cheapest SWAC project costs $0.0185/KWh$_t$ and is located in Nauru, Pacific Ocean.

1. Introduction

In warmer climates, particularly the low-latitudes of Latin America, South and Southeast Asia, demand for air conditioning is surging [1]. Air conditioning already accounts for about 40% of power use in Mumbai, India. More than half of Saudi Arabia's peak summer power consumption, generated by burning 1bn barrels of oil a year, also goes on air conditioning [2]. The Intergovernmental Panel on Climate Change estimates that demand for residential air conditioning alone will rise from 300 terawatt hours per year (TWh/year) in 2000 to 4,000 in 2050 and 10,000 by 2100 [2]. Energy costs can be particularly high for air conditioning systems in island locations, where electricity costs are usually high due to the reliance on imported oil as the main generation resource.

The deep ocean is by comparison 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 base load district cooling technology that uses deep cold seawater that can be as cold as 3-5°C, even in the tropics [3]. SWAC replaces the chillers used in conventional AC systems, greatly reducing the electricity consumption and cooling costs [4, 5]. Given that the capital costs are high, a SWAC plant should operate as much as possible at its maximum capacity. It is proposed for locations with year-round high temperatures (around 28°C) in the inter-tropical regions and where seafloor bathymetry allows a reasonably short cold seawater intake pipeline [6].

This paper investigates the world potential for SWAC by focusing on four key aspects, the pipeline length, the capacity factor of the SWAC project, the depth required to reach seawater at 5°C and cooling costs estimates. The pipeline length influences mainly capital costs, but also operation costs of SWAC projects and should be as short as possible. The ambient temperature influences the need for cooling, which is proportional to the capacity factor of SWAC projects and should be as high as possible. The depth required to reach seawater with 5°C impacts mainly on the operation costs, given the higher energy required to pump the deep seawater, but also in capital costs due to the need for a deeper excavation of the seawater pump-station. This paper performs a quantitative costs analysis of SWAC projects taking into account the three important aspects of the technology, capacity factor, offshore pipeline length, and seawater extraction depth.

The process of seawater air conditioning consists of extracting seawater from the ocean, using it for district cooling and returning the seawater to the ocean. Figure 1 presents the basic configuration of a 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 is used to exchange heat from the seawater and district cooling or heating system; (5) the district cooling or heating system distributes the cold or warm water from the SWAC plant to the cooling demand. This paper focus in deep seawater air conditioning for cooling purposes. For more details refer to [7, 8, 3, 9].

Figure 1: Seawater air conditioning scheme main parts. Adapted from Honolulu Seawater Air Conditioning (http://honoluluswac.com/) [10].

Seawater air conditioning systems can be divided into shallow and deep seawater. The main difference between both technologies is the depth at which seawater is extracted, which is directly related to the seawater temperature profile. Shallow seawater air conditioning is mainly applied for cooling and/or heating of building in locations in mid to high latitudes. Although the applications of shallow seawater are not so common in western countries, seawater is generally used in Asian cities by the coast in water-cooled refrigeration systems [11]. Deep seawater air conditioning requires long pipelines to reach the deep seawater and are only applied for cooling purposes at low to mid latitude locations. Typical applications and operational temperature profiles of shallow and deep seawater air conditioning are presented in Table 1 [12, 13, 14].

Table 1: Typical applications of shallow and deep seawater air conditioning.

To illustrate the substantial potential of SWAC, Table 2 compares the amount of cooling energy potential in the deep ocean seawater with other renewable electricity generation sources. Comparing the energetic potential of deep seawater and hydropower for cooling purposes, 1 m^3/s of deep seawater with a 10^oC temperature change is equivalent to a hydropower plant with a generation head of 186 meters and ten times the flow, or equivalent to a 488,000 m^2 solar power plant, or equivalent to 21 wind turbines. Note that SWAC processes also require electricity to operate, especially for pumping the deep seawater to the coast and to operate the district cooling process. It is estimated that the COP (Coefficient of performance, unit of cold created per unit of electricity consumed) of high efficient conventional coolers COP is 4 and the COP of SWAC systems is around 13 [7]. This COP is calculated using the average cooling load provided by the SWAC system (for example, 16 MW) divided by the average electricity required to operate the SWAC system, i.e. the seawater and fresh water pumps (for example, 1.2 MW) [7].

Table 2: Comparison of deep ocean seawater with other cooling sources.

Figure 2 presents the locations of deep and shallow SWAC projects around the world. Shallow SWAC integrated with district cooling and heating exists in Toronto, Halifax (Canada), Amsterdam (Netherlands), Stockholm (Sweden), Hamina (Finland), New York (USA) [16] and Copenhagen (Denmark) [17]: It is noticeable that those projects were developed in non tropical regions. In some cases the cooling system only operates in a few months during summertime. That is the case of Toronto's SWAC system, which draws water from Lake Ontario through pipelines extending 5 km into the lake, reaching a depth of 115 m. This shallow SWAC system is part of an integrated district cooling system that covers Toronto's financial district and also supplies water to the municipal drinking water system. Canada has two other operational systems at Halifax, Nova Scotia, which cool office buildings since

1986 and 2010, respectively. The SWAC systems in the Zuidas (2006) and Zuidoost (2009) districts of Amsterdam draw cold lake water from the nearby lake Nieuwe Meer at a depth of 30 m. Those systems are capable of cooling a load of 60 MW and 64 MW, respectively. Stockholm's SWAC system began operation in 1995 with an innovative characteristic: the use of a cold-water storage facility.At night, when the demand for cooling is lower, the facility can store any excess cold water and later supply that water when demand increases during the warmer hours of the day. In the case of Hamina (Finland) the SWAC system cools a data center, which has a thermal load that is constant throughout the year. Data centers are very energy-intensive buildings and already represent 2% of the electricity consumption in some developed countries [18]. Besides computers and electronics, their main energy consumption (20 to 50%) is due to cooling and ventilation, which are necessary to dissipate the heat produced in the circuits. As the Hamina case shows, that cooling energy can be provided by SWAC in a cost-effective manner. Deep cold waters have also been used to cool educational buildings. In Cornell University, the electricity needed for air conditioning was cut by 87% in 1999 with the use of Cayuga Lake (New York) as a heat sink to operate the central chilled water system for the campus and to also provide cooling to the Ithaca City School District [16].

There are also nice examples of shallow SWAC integrated with district cooling and heating in Asian cities such as Dalian, Hong Kong (China) that provides air conditioning to the Excelsior Hotel and the HSBC office tower [19, 20, 21, 22], Nagasaki (Japan) [23] and Seoul (South Korea) [24, 25]. In South America, the "Museum of Tomorrow" (2015) in Rio de Janeiro (Brazil) outstands for its high efficiency chillers and for using seawater from the Guanabara Bay [26]. In Manama (Bahrain) seawater is drawn from the Arabian Gulf to cool the Bahrain Diplomatic Area District Cooling Project's air conditioning plant. The system was designed in 2005 featuring a 1.6 m diameter, 683 m long intake pipeline and a 1.4 m diameter, 1556 m long outfall pipeline with a 20 port diffuser, operating at a flow rate of 3.79 m^3 per second [12, 5].

Meanwhile, deep SWAC has been applied for cooling services in Keahole Point, Honolulu (Hawaii) [27, 28, 9, 12], Nassau (Bahamas) [16], Aruba [9], Port Louis (Mauritius) [29, 30, 31, 17, 32], Bora Bora (French Polynesia) [9, 3], Tetiatoa Atoll (French Polynesia) [9], Curação [33], Reunion Island

(France) [34]. Deep SWAC has also been considered in Montego Bay (Jamaica) [7], Puerto Plata (Dominican Republic) [7] and other Caribbean Islands [7], Florida and California (USA) [35, 36, 37], Brazilian Coast [38], San Andres (Colombia) [39], Hal Far (Malta) [40], Taitung (Taiwan) [41], Oman [42], Ghana [43] and Qesm Hurghada (Egypt) [8]. Notice that the last project was disregarded because the temperature of the deep Red sea is around 20^{o}C as presented in Figure 6.

Tropical islands offer some of the nicest examples of SWAC. The Hawaiian Islands, located on the equator and with a narrow continental shelf offer indeed several privileged locations in the application of this technology. The Natural Energy Laboratory of Hawaii Authority (NELHA) pioneered SWAC in 1993 at their Keahole Point's facility on the Island of Kona. The project included the installation of a 1.0 m diameter, 2 km large, high density polyethylene pipe capable of delivering 840 l/s of cold seawater [44]. The primary purpose at the time was to research OTEC (Ocean Thermal Energy Conversion) as a renewable source to produce electricity.It was soon realized that utilizing this cold seawater as the primary chilled water resource would provide great economic and environmental gains. Despite no commercial-scale OTEC plant has been built since that project was launched, the deep seawater still cools the buildings at NELHA and provides nutrient rich seawater for fish farming, agriculture and bottled water production. Nowadays the Hawaii Ocean Science and Technology-Seacoast Test Facility at Keahole Point, Honolulu (Hawaii) extracts both shallow (warm) and deep (cold) ocean waters for use in open-cycle OTEC experiments and in commercial mariculture [27, 28, 9, 12]. Other remarkable projects in the Pacific are the Tetiatoa Atoll [9] and Bora Bora in the French Polynesia [9, 3], where cold ocean water is passed through a heat exchanger where it cools freshwater that is pumped to cool resort and spa buildings. The project was completed in 2006 and relies on a 2000 m long pipeline going to 900 m depth on a seabed with slopes up to 60 degrees. Tourism infrastructure located on islands seems to be another interesting field for SWAC. In the Caribbean Sea, this is the case of hotels and casinos in Nassau (Bahamas) [16], or Aruba [9] and also Curação [33] projects, the latter aiming to supply cooling to 4 hotels and a power plant through a 0.915 m, 6 km long intake pipeline extending to an intake depth of 850 m. Finally, in the Indian Ocean, the most remarkable projects regard the islands of Mauritius and Reunion. In Port Louis (Mauritius) a SWAC project is being developed [29, 30, 31, 17, 32]. That project would replace the traditional air conditioning system, which demands 30

MW of electrical power, with 44 MW of cooling power from cold seawater pumped from 6 km offshore. As the necessary power for the SWAC pumps is projected to be 4 MW, switching from the traditional system to SWAC would cut the electrical power needed for cooling by 26 MW [45]. At the Reunion Island (France), SWAC has been proposed for a hospital and for the district cooling system of the main city, Saint Denis. The latter consists in a pipeline of 6 km offshore at a depth of 1100 m. It is estimated that in those projects, SWAC would cut electricity costs by 50% and 80%, respectively, in comparison with traditional cooling systems [34].

Table 3 presents a review of the benefits and challenges of SWAC, including the main references that address each characteristic. More details on SWAC projects can be found in [46, 47].

Figure 2: Deep and shallow SWAC projects under construction or operation around the world.

Table 3: Review of benefits and challenges of SWAC.

This paper is divided into five sections. Section 2 presents the main component for estimating the world potential of SWAC, presents the data applied in the study and explains the methodology applied in the paper. Section 3 presents the results of this paper, which are the required ocean depth to reach seawater below 5^{o}C temperature, the pipeline lengths and the capacity factor of SWAC projects. Section 4 discusses the methodologies and resuts on the paper. Section 5 concludes the paper.

2. Data and Methodology

The thermocline is a layer in the ocean that divides the surface ocean and the deep ocean [54, 55, 56]. It is where the warm seawater at the surface mixes with the deep cold seawater. The cold seawater on the bottom of the ocean results from the downward displacement of cold seawater from high latitudes, i.e. the North and South poles, due to the higher density of the cold seawater, as it is shown in Figure 3. The thermocline acts like a lid on the deep ocean, keeping the cold, CO_2 and nutrient-rich deep water from returning to the surface. Typical temperature variation with depth profiles of the open ocean in tropical and equatorial latitudes, and middle latitudes, focusing on western and eastern North Pacific are presented in Figure 4 [54], where the temperature at 700 to 2,000 meters depth is approximately 5^{o}C. This rapid change in temperature with depth has been extensively studied for electricity generation with ocean thermal energy conversion [57, 58, 59, 60]. Figure 4 also includes the change in density with depth, which is important to design the excavation depth of the seawater pumping station of a SWAC system and the energy required to pump water from the deep ocean. It should be noted that the world's temperature and salinity vary considerably more than the density of the seawater.

Figure 3: Origin of the world's cold, deep seawater [61].

Figure 4: Typical temperature and density variation with water depth in the open ocean. Adapted from [62, 54].

Some deep seas around the world do not have the temperature variation profile as presented in Figure 4. This happens where the seas are not connected to the deep ocean (depths higher than 1,000 to 1,500 meters), for example, in the Mediterranean Sea [63], the Sulu, Visayan and Bohol Seas in Southwestern Philippines [64] (as shown in Figure 5) and the Red Sea between the Middle East and Africa [65].

Figure 5: Temperature variation with depth of the Sulu Sea [64].

Figure 6 presents the variation of the ocean temperature at different coordinates and depths. Figure 6 (a) and (b) presents the temperature of the deep ocean at 700 meters depth during the winter and the summer in the Northern Hemisphere, respectively. As it can be seen, seasonal changes have a very small impact on ocean temperatures at this depth. Figure 6 (c) presents the ocean temperature at 1,000 meters depth and Figure 6 (d) presents the ocean temperature at 1,300 meters depth. The lower the depth, the lower the seawater temperature. This data is used to develop a map with the depths required to reach a seawater temperature of 5^{o}C or less (commonly used in SWAC projects), with the intention of estimating the world potential of SWAC.

Figure 6: World's ocean temperature in degree Celsius at 700 meters depth during the (a) winter and (b) summer in the Northern Hemisphere, and at (c) 1000 and (d) 1300 meters depth [53].

The SWAC world potential model, developed in this study, is divided into four steps as presented in Figure 7. Step 1 uses available world ocean temperature data at different depths to find the depth required to reach seawater at 5°C or less. Step 2 used the bathymetry data of the world ocean to estimate the length of the pipeline to connect the coast to the required depth estimated previously. Firstly, it looks for points on the coast with absolute heights of 0 to 10 meters, then it looks for ocean depths required to reach seawater at 5°C or less within a radius of 1 km, assuming that the pipeline in a straight line lying on the seabed. If 1 km is not enough to reach a seawater temperature of 5°C, the pipeline length is increased in step of 1 km up to 30 km. The depth is neglected when estimating the pipeline length. The selected shortest pipelines in the world are presented in the map with 2.5 arc degree resolution to facilitate the presentation of the results. Step 3 intends to estimate the capacity factor for SWAC projects, assuming that it is designed to cool the ambient temperature from 30 to 20°C. Surface air temperature data is used to count the hours from 2008 to 2017 that the temperature was above 20, 22, 24, 26, 28 and 30°C. This data is used to estimate the capacity factor with Eq. 3. Step 4 consists of comparing the selected SWAC projects with the shortest pipelines, with their capacity factor and depth required to reach a temperature of 5°C. Cost estimations are then performed for the proposed SWAC projects. Information on the data input used in the model is presented in Table 4. More details of each task are presented in Table 5. More details on the cost estimations are in the Appendix section.

Figure 7: SWAC world potential model framework (Figure (a) is from [53], (c) [66] and (f) [67]).

Table 4: Data input into the SWAC world potential model.

Table 5: Data based used to estimate the world potential for SWAC.

The SWAC design proposed in this work intends to cool ambient air temperature from 30°C to 20°C for the reasons below:

1. It is important to have a standard design to compare SWAC projects around the world.
2. The selected minimum design temperature of the cooling system is 20°C because this temperature often used in commercial building and hotels [73]. Additionally, SWAC projects have low operation costs, thus, their cooling services should be used as much as possible once installed.
3. The selected maximum design temperature of the cooling system is 30°C because it should be as high as possible to increase the viability of SWAC projects. However, a high capacity factor

is also required and a SWAC project designed to cool temperatures above 30°C would have a small capacity factor.

The capacity factor CP during the studied period (h_0 to h_f) is the average value among all the hourly capacity values (Eq. 1):

Eq. 1 $$CP\ (\%) = \frac{1}{h}\sum_{h_i = h_0}^{h_f} CP_{hi}(\%)$$

The capacity value of each hour, CP_{hi}, is calculated by comparing the observed surface air temperature at that hour, T_{hi}, with a set of temperatures, which are T_i = 22°C, 24°C, 26°C, 28°C and 30°C. This equation checks if the temperature at a given hour is above set thresholds. For example, if the temperature is 30°C, then the capacity utilization at that hour is 100%, if it is 28°C, 80%, if it is 26°C, 60% and so on.

Eq. 2 $$CP_{hi}(\%) = \frac{100}{s}\sum_{T_i = T_{min}}^{T_{max}} \left(T_{hi} \cdot T_i\right)$$

$$T_{hi} \cdot T_i = 1\ if\ T_{h_i} \geq T_i$$
$$T_{hi} \cdot T_i = 0\ if\ T_{h_i} < T_i$$

The two equations above can be combined into a single one, as follows:

Eq. 3 $$CP\ (\%) = \frac{100}{s \cdot h}\sum_{h_i = h_0}^{h_f} \sum_{T_i = T_{min}}^{T_{max}} \left(T_{hi} \cdot T_i\right)$$

Where:

CP is the capacity factor of the proposed SWAC project in %.

h_i is the hour under analysis.

h_0 is the initial hour under analysis, assumed to be 00:00 01/01/2008.

h_f is the final hour under analysis, assumed to be 23:00 31/12/2017

T_{min} is the minimum temperature for the SWAC design, assumed to be 20+2°C.

T_{max} is the maximum temperature for SWAC design, assumed to be 30°C.

T_i are the temperatures utilized in the iteration, assumed to be 22, 24, 26, 28, 30°C.

T_{hi} is the observed surface air temperature at a given hour in °C.

s is the number of temperature iterations from 20 to 30°C, which is equal to 5.

h is the number of hours under analysis, assumed to be 87672, from 01/01/2008 to 31/12/2017.

3. Results

Figure 8 presents the results from Step 1 of the SWAC world potential model, which is the ocean depth required to reach seawater with 5°C or less with 1 arc degree resolution. These results show that the Southern hemisphere of the Atlantic Ocean requires a depth of 700 to 900 meters to reach 5°C seawater. The higher section of the Northern Hemisphere of the Atlantic Ocean requires a depth of 1300 to 2000 meters, with the highest depth close to the exit of the Mediterranean Sea. Note that the ocean facing into the Caribbean Sea the depth varies from 1000 to 1100 meters. The Indian Ocean varies from 1750 meters to 1000, with the higher depth close to the Persian Gulf and the Red Sea. The Pacific Ocean has a relatively homogeneous distribution varying from 800 to 1200 meters, with the equator raying from 900 to 1100 meters. This shows that the east coast of South America and mid-west coast of Africa are the shallowest intertropical regions to reach the deep cold seawater.

Figure 8: Depth required to reach seawater with 5°C or less.

Note that Figure 8 excludes seas with warm deep waters, as explained in Figure 5, for example, the Mediterranean, Sulu, Visayan, Bohol and Red seas. Notice that the Gulf of Mexico is appropriate for SWAC because the Gulf Sea is in contact with the deep Atlantic Ocean [74]. The Sea of Japan is not in contact with the deep sea, however it is located in high latitudes. Its temperature below 30 m depth is lower than 5°C [75] and, thus, SWAC could be applied.

Figure 9 presents the results from Step 2 of the SWAC world potential model, which are the possible SWAC projects around the world. The area in green represents the islands and continents, the area in blue represents the oceans and the lines in yellow represents the pipelines. The pipeline length varies from 1 km, which corresponds to 1 pixel in the figure and 30 km. The scales are included in each figure for pipeline length measurements. A more comprehensive presentation of the pipeline lengths is shown in Figure 12 (a).

Figure 9: Maps with potential SWAC projects around the world.

Figure 10 presents the results from Step 3 of the SWAC world potential model, which is the percentage number of hours in which the surface air temperature around the world is higher than 22°C (Figure 10 (a)), 26 °C (Figure 10 (b)) and 30 °C (Figure 10 (c)). These data are used to estimate the capacity factor of the SWAC projects, shown in Figure 11. As it can be seen in Figure 11, most inter-tropical areas have high demand for base load SWAC cooling services, apart from the west coast of South America, and the high and low latitudes of West Africa.

Figure 10: World maps with the number of hours from 2008 until 2017, in which the surface air temperature is above (a) 22°C (b) 26 °C (c) 30 °C.

Figure 11: SWAC capacity factor assuming a project designed to cool from 30°C to 20°C.

The final step of the SWAC world potential model consists of comparing the pipeline length, SWAC capacity factor and seawater depth extraction. The SWAC projects with the smallest pipeline length in a 2.5 degrees resolution were selected (Figure 12 (a)) and compared with their respective capacity factor (Figure 12 (b)) and seawater extraction depth (Figure 12 (c)). The pixels in red represent the locations where the parameter supports the implementation of SWAC. The figures give a good overall idea of where SWAC is likely viable. A more detailed analysis of the results is presented in the conclusion section.

Figure 12: SWAC world potential maps represented by the (a) length of the pipeline, (b) capacity factor and (c) depth where the seawater is extracted.

A quantitative cost analysis of the SWAC projects around the world is presented in Figure 13. The cost estimates in this analysis is presented in the Appendix section and includes the varying capacity factors, pipeline lengths and seawater extraction depths. It shows that there are 112 location where the costs are lower than \$0.1/KWh_t higher than \$0.05/KWh_t, 332 location where the costs are lower than \$0.05/KWh_t higher than \$0.02/KWh_t, and 17 location where the costs are lower than \$0.02/KWh_t. These projects assume a fixed cooling demand of 24 MW per project. The cheapest location is \$0.0185/KWh_t and is located in Nauru, an small island in the Pacific Ocean. It should be noted that the costs of SWAC considerably reduces with the increase in cooling demand.

Figure 13: SWAC projects cost estimate in dollars per KWh of cooling.

4. Discussion

The cost for cooling with conventional AC systems consume a lot of electricity. This is an issue especially on islands states, where the electricity prices are high. For example, in Puerto Plata, where the electricity costs are \$0.32/KWh, the costs of cooling are \$0.08/KWh_t [7] (including capital and operation costs). The SWAC solution would cost \$ 0.042/KWht, which is 48% less than conventional technologies. In Nauru, assuming the same electricity cost, the SWAC solution would be \$0.0185/KWh_t, which is 77% less compared with conventional technologies. The cost estimate in this paper assume a high costs of electricity. This is because SWAC is most likely to be viable in small islands, where the costs of electricity for cooling are high.

This paper assumes that the length of the pipeline is the distance from the coast until a depth where the sea temperature is below 5^oC. Thus, if the cooling demand is 10 km from the coast, the pipeline length will be 10 km longer than the one presented in this paper. The pipeline in the coast in SWAC projects, after the heat exchanger, is called district cooling distribution system. This consists of a reasonable part of the costs of SWAC projects. Thus, to increase the viability of SWAC projects the cooling demand should be close to the coast.

The SWAC capacity factor is calculated with Equation 3 using global hourly temperature data from 2008 to 2017. Note that the capacity factor analyzed in this study only takes into account the supply of cooling with the variation in ambient temperature. However, the capacity factor is also highly dependent on the demand for cooling. This demand for cooling varies considerably with the customer. For example, islands with strong tourism industry have considerable weekly, monthly and seasonal cooling demand variations, which would have a considerate impact on the actual capacity factor of a SWAC plant. Another important issue to consider is that the cooling demand of the SWAC projects are assumed to be 24 MW. Given that the costs of cooling considerably reduces with the increase in cooling demand, it should be noted that the costs in Figure 13 can considerably reduce with the increase in cooling demand.

SWAC is considered to be a renewable source of energy in this paper. However, this is only the case if the electricity used to operate the seawater and freshwater pumps come from renewable sources of energy.

5. Conclusions

This paper concludes that deep seawater has large potential in inter-tropical regions, especially in small tropical islands with high electricity costs and with a favorable seafloor bathymetry that allows the cold seawater inlet pipeline to be reasonably short. The world potential for SWAC presented in this paper focuses on four main aspects, the pipeline length, the estimated capacity factor of the SWAC project, the depth to reach seawater at 5^{o}C and the cost estimates.. According to Figure 12 and Figure 13, possible viable locations for the construction of SWAC projects, with a cost lower than \$0.04 KWh_t, are the intertropical islands in the Caribbean, Pacific and Indian Oceans, and the Fernando de Noronha, São Tomé and Principe in the Atlantic Ocean. Hawaii's potential is limited to few locations due to the low SWAC capacity factor. The continental and medium sizes islands potential for SWAC can be seen in the West Coast of Mexico, Colombia, Northeast of Brazil, Togo, Yemen, Madagascar, Sri Lanka, Indonesia, Philippines and Papua New Guinea.

This assessment of SWAC world potential model has not included population density and the demand for cooling in the analysis, which will be assessed in future work and is an important component for a full techno-economic feasibility assessment..

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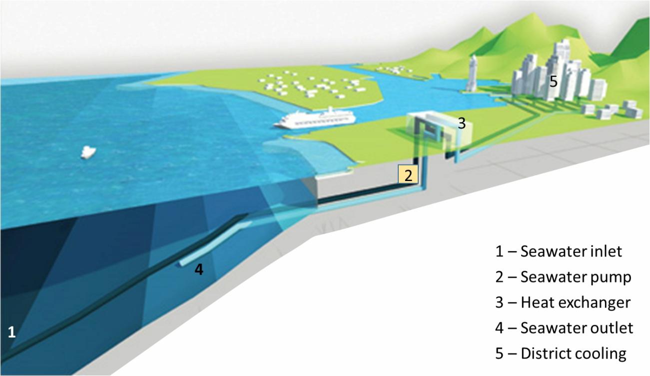
8. Appendix

The cost estimate performed in this paper assumes values of the SWAC project developed for Puerto Plata in [7] as a basis for the comparison. This assumes that the following values constant for all projects: cooling load (24 MW), seawater velocity in the off-shore pipelines (0.56 m/s, which results in a head loss by friction in the pipeline length of 4.4 m per km of pipeline), and interest rate (11.5%). The costs of the coastal section of the SWAC project are assumed to remain constant and equal to $ 7,688,000 for the pump station, $ 3,931,000 for the heat exchanger, $ 15,461,000 for the distribution system. For more details on other parameters please refer to [7].

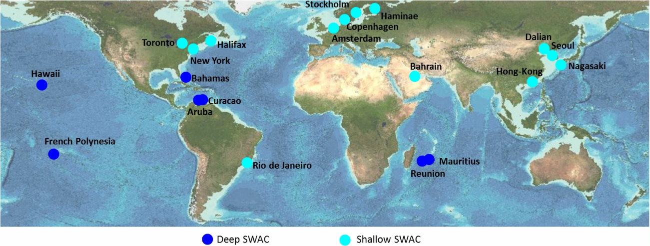
The density variation to estimate the head loss due to density difference was taken from Figure 4 and is assumed not to vary with location. The head loss due to friction for seawater extraction at depths of 700, 1000 and 1500 meters are 1.11, 1.97 and 3.47 meters respectively. The cost of offshore pipeline, originally set at $4,341/km, is assumed to vary linearly with the length of the pipeline. Heat losses through the pipeline and cost changes in the pump station are not considered.

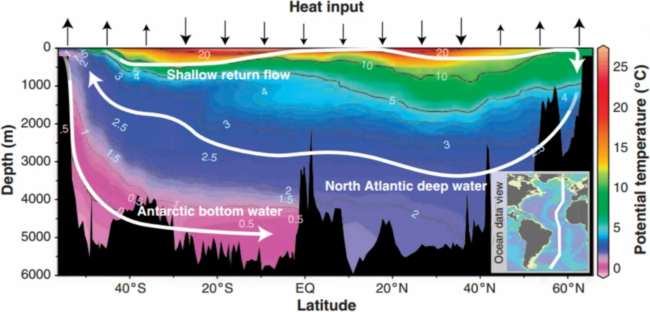
The cost of electricity is set at $0.32/KWh$_e$. This is a high value for continental locations, but appropriate for small islands. The cost of electricity consumption in the SWAC project is set to vary from $ 16,677,000 (assuming 20 years of operation of the plant) linearly with the head loss due to density difference and the head loss due to friction in the pipeline length (which varies with the length of the pipeline).

The final cost of the SWAC project in Puerto Plata is equivalent to $ 83 million dollars, assuming 20 years of operation, which is equivalent to a cost of cooling of $ 0.0415/KWh$_t$. The same cost ration is applied to the other projects. The final cost, including the fixed coastal costs, are then adjusted to the capacity factor of each location compared with the capacity factor from Puerto Plata, which is equal to 0.65 as in [7] and Figure 12.

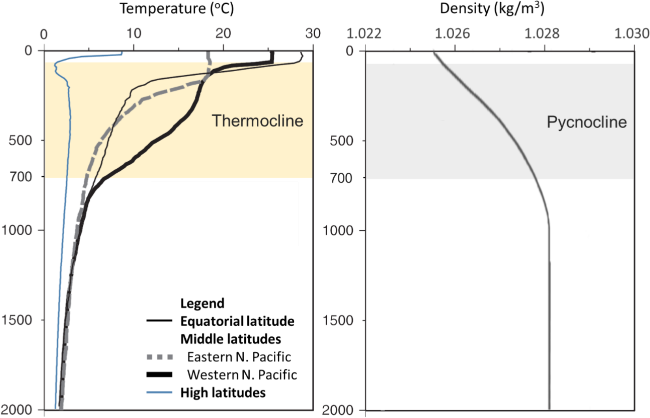


1
2
3
4
5
1 – Seawater inlet
2 – Seawater pump
3 – Heat exchanger
4 – Seawater outlet
5 – District cooling

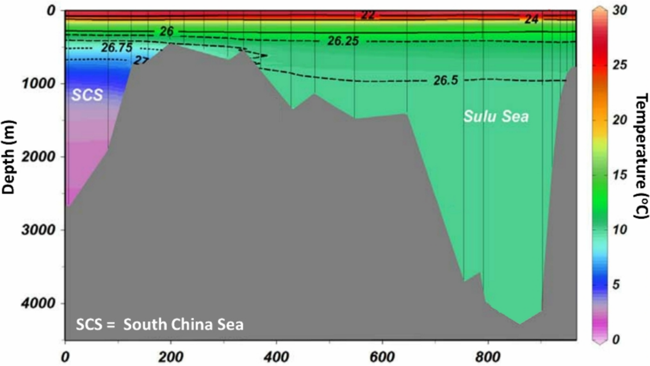

Stockholm
Haminae
Copenhagen
Amsterdam
Toronto
Halifax
New York
Dalian
Seoul
Nagasaki
Hong-Kong
Bahrain
Hawaii
Bahamas
Curacao
Aruba
French Polynesia
Rio de Janeiro
Mauritius
Reunion
Deep SWAC
Shallow SWAC



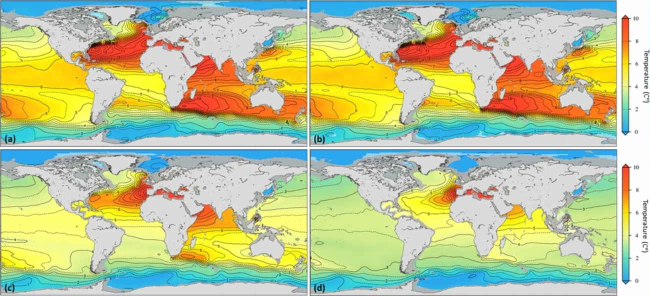
Heat input
Shallow return flow
North Atlantic deep water
Antarctic bottom water
Ocean data view
Depth (m)
Latitude
Potential temperature (°C)
40°S
20°S
EQ
20°N
40°N
60°N

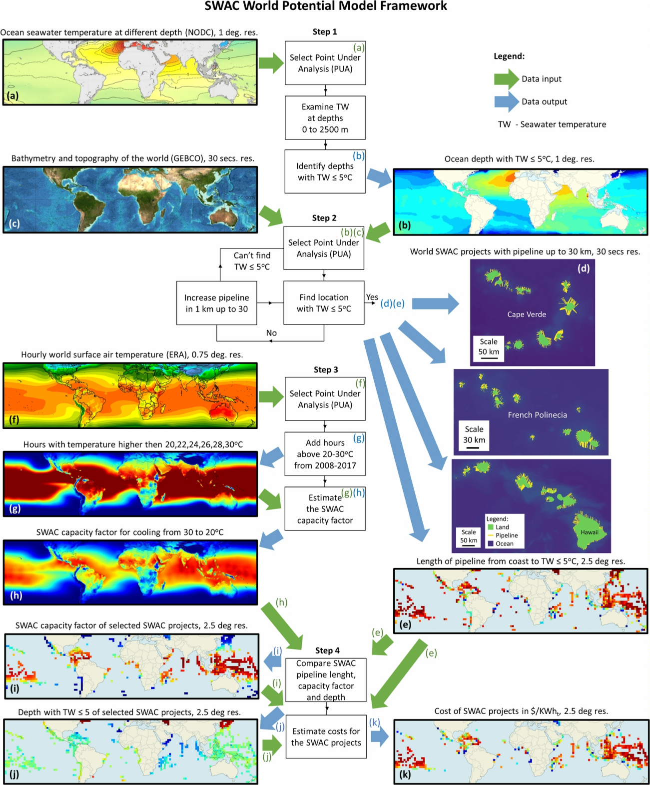


Temperature (°C)
0
10
20
30
0
500
700
1000
1500
2000
Thermocline
Legend
Equatorial latitude
Middle latitudes
Eastern N. Pacific
Western N. Pacific
High latitudes
Density (kg/m³)
1.022
1.026
1.028
1.030
Pycnocline

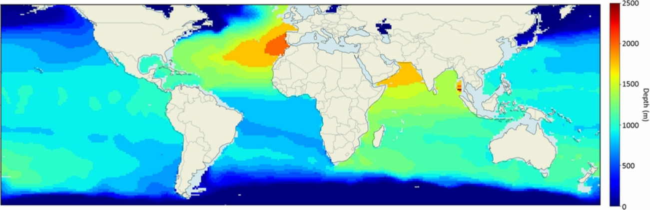


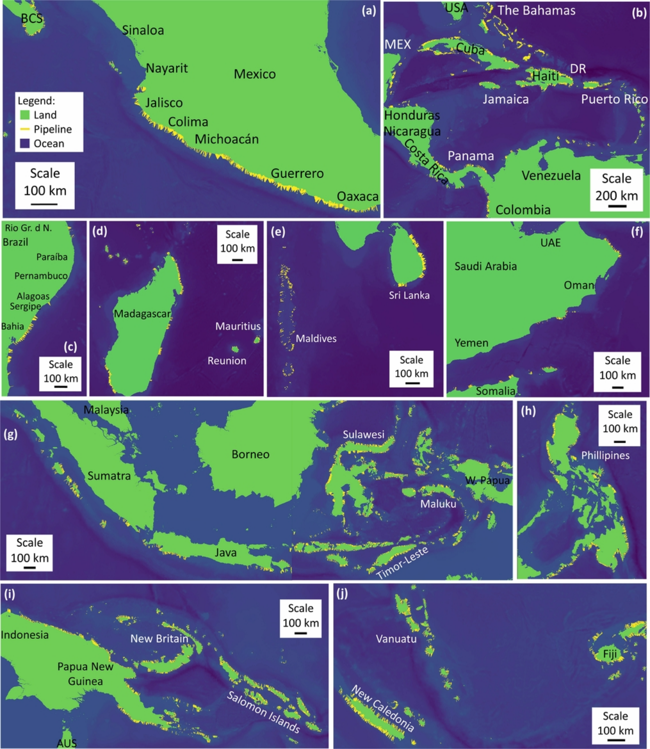
0
1000
2000
3000
4000
Depth (m)
0
200
400
600
800
22
24
26
26.25
26.75
27
26.5
SCS
Sulu Sea
SCS = South China Sea
Temperature (°C)
30
25
20
15
10
5
0


(a)
(b)
(c)
(d)
Temperature (C°)
10
8
6
4
2
0
Temperature (C°)
10
8
6
4
2
0

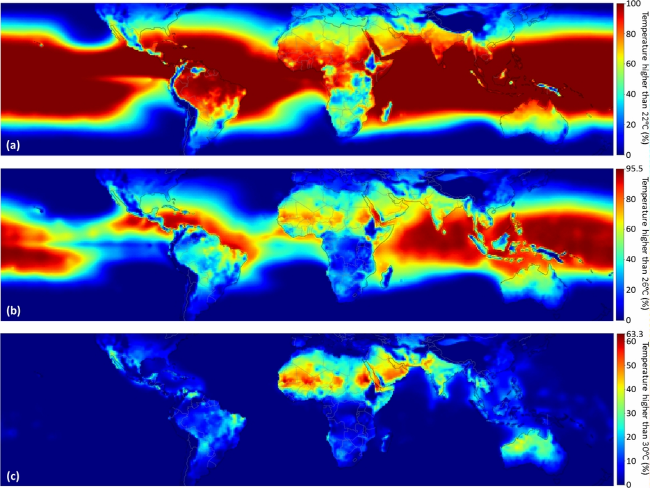


SWAC World Potential Model Framework
Ocean seawater temperature at different depth (NODC), 1 deg. res.
(a)
Step 1
(a)
Select Point Under Analysis (PUA)
Examine TW at depths 0 to 2500 m
(b)
Identify depths with TW ≤ 5°C
Legend:
Data input
Data output
TW - Seawater temperature
Bathymetry and topography of the world (GEBCO), 30 secs. res.
(c)
Ocean depth with TW ≤ 5°C, 1 deg. res.
(b)
Step 2
(b)(c)
Select Point Under Analysis (PUA)
Can't find TW ≤ 5°C
Increase pipeline in 1 km up to 30
Find location with TW ≤ 5°C
Yes
(d)(e)
No
World SWAC projects with pipeline up to 30 km, 30 secs res.
(d)
Cape Verde
Scale
50 km
French Polinecia
Scale
30 km
Scale
50 km
Legend:
Land
Pipeline
Ocean
Hawaii
Hourly world surface air temperature (ERA), 0.75 deg. res.
(f)
Step 3
(f)
Select Point Under Analysis (PUA)
(g)
Add hours above 20-30°C from 2008-2017
Hours with temperature higher then 20,22,24,26,28,30°C
(g)
(g)(h)
Estimate the SWAC capacity factor
SWAC capacity factor for cooling from 30 to 20°C
(h)
Length of pipeline from coast to TW ≤ 5°C, 2.5 deg res.
(e)
(h)
(e)
(e)
SWAC capacity factor of selected SWAC projects, 2.5 deg res.
(i)
Step 4
(i)
Compare SWAC pipeline lenght, capacity factor and depth
(i)
Depth with TW ≤ 5 of selected SWAC projects, 2.5 deg res.
(j)
(j)
Estimate costs for the SWAC projects
(j)
(k)
Cost of SWAC projects in \$/KWh$_t$, 2.5 deg res.
(k)

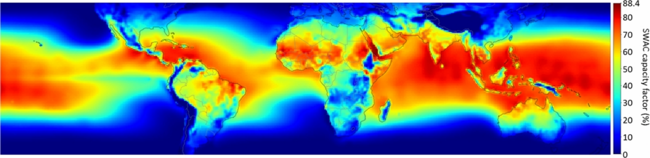

2500
2000
1500
1000
500
0
Depth (m)

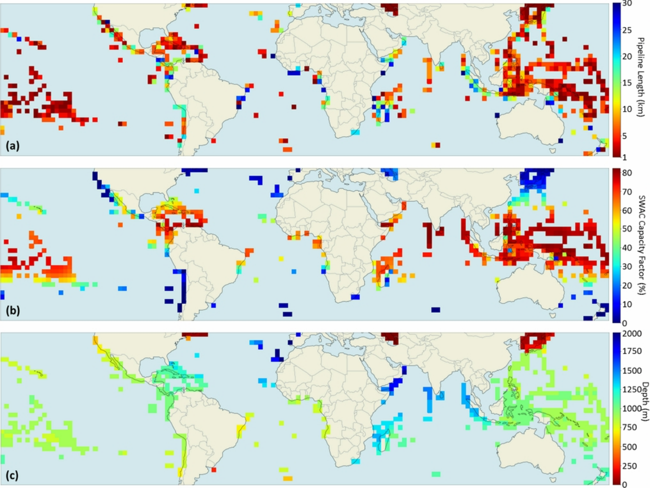


(a)
BCS
Sinaloa
Nayarit
Mexico
Jalisco
Colima
Michoacán
Guerrero
Oaxaca
Legend:
Land
Pipeline
Ocean
Scale
100 km
(b)
USA
The Bahamas
MEX
Cuba
DR
Haiti
Jamaica
Puerto Rico
Honduras
Nicaragua
Costa Rica
Panama
Venezuela
Colombia
Scale
200 km
Rio Gr. d N.
Brazil
Paraíba
Pernambuco
Alagoas
Sergipe
Bahia
(c)
Scale
100 km
(d)
Scale
100 km
Madagascar
Mauritius
Reunion
(e)
Sri Lanka
Maldives
Scale
100 km
(f)
UAE
Saudi Arabia
Oman
Yemen
Somalia
Scale
100 km
Malaysia
(g)
Borneo
Sulawesi
Sumatra
W. Papua
Maluku
Java
Timor-Leste
Scale
100 km
(h)
Scale
100 km
Phillipines
(i)
Scale
100 km
Indonesia
New Britain
Papua New
Guinea
Salomon Islands
AUS
(j)
Vanuatu
Fiji
New Caledonia
Scale
100 km



(a)
Temperature higher than 22°C (%)
0
20
40
60
80
100
(b)
Temperature higher than 26°C (%)
0
20
40
60
80
95.5
(c)
Temperature higher than 30°C (%)
0
10
20
30
40
50
60
63.3


88.4
80
70
60
50
40
30
20
10
0
SWAC capacity factor (%)


(a)
Pipeline Length (km)
30
25
20
15
10
5
1
(b)
SWAC Capacity Factor (%)
80
70
60
50
40
30
20
10
0
(c)
Depth (m)
2000
1750
1500
1250
1000
750
500
250
0

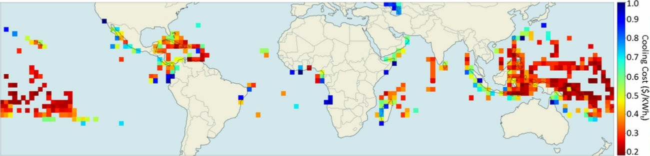

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Cooling Cost ($/kWh$_t$)

Table 1: Typical applications of shallow and deep seawater air conditioning.

Seawater Air Conditioning	**Latitude**	**Seawater Temp. (°C)**		**Atmospheric Temp. (°C)**		**Service**	
		Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Shallow 0 to 50 depth	High (70°-45°)	~10 to 20	~3 to 8	~15 to 30	~-10 to 5	Cooling	Heating
	Medium (45°-21°)	~15 to 20	~8 to 15	~20 to 35	~0 to 15	Cooling	Heating
	Inter-Tropical (0°-21°)	~20 to 35	~20 to 30	~25 to 35	~20 to 30	Cooling	Cooling
Deep 700 to 2.000 depth	High (70°-45°)	~2 to 5	~2 to 5	~15 to 30	~-10 to 5	-	-
	Medium (45°-21°)	~2 to 5	~2 to 5	~20 to 30	~0 to 15	Cooling	-
	Inter-Tropical (0°-21°)	~2 to 5	~2 to 5	~25 to 35	~20 to 30	Cooling	Cooling

Table 2: Comparison of deep ocean seawater with other cooling sources.

Source of energy	Driving force	Quantity	Electricity generation/ consumption	Cooling potential
Deep seawater	Temperature Difference: $\Delta T = 10^oC$	Deep Seawater Flow: 1 m^3/s	-1 MW_e[i, ii]	10^oC x 0.004 MJ/kg.K[iii] x 1 m^3/s x 1,028 kg/m^3[iv] = 41 MW_t[v]
Hydropower	Height: ΔH = 186 m at 90% efficiency	Dam Turbine Flow: 10 m^3/s	186 m x 9.8 m^3/s x 10 m^3/s x 0.9 = 16,4 MW_e	16,4 MW_e x 2.5[vi] (COP) = 41 MW_t
Photovoltaic cells	Solar Irradiation: 0.24 kW_e/m^2 at 14% capacity factor	Photovoltaic Cells: Area 488,000 m^2	0.24 kW_e/m^2 x 488,000 m^2 x 0.14 = 16,4 MW_e	16,4 MW_e x 2.5 (COP) = 41 MW_t
Wind power	Wind Generation: 2 MW_e at 40% capacity factor	Number of wind turbines: 21 turbines	2 MW_e x 0.4 x 21 = 16,4 MW_e	16,4 MW_e x 2.5 (COP) = 41 MW_t

[i] Assuming the energy for seawater pump and district cooling system [7].
[ii] Megawatts of electricity consumption.
[iii] The specific heat of seawater at 0^oC with 35 g of salt/kg of water is 0.004 MJ/kg.K [15].
[iv] The density of seawater at 5^oC and with 35 g of salt/kg of water is 1,028 kg/m^3 [15].
[v] Megawatts of thermal energy for cooling.
[vi] Assuming that the conversion of electricity to cooling power has a Coefficient of Performance (COP) of 2.5. The COP of 2.5 is relatively conservative by modern efficiency standards.

Table 3: Review of benefits and challenges of SWAC.

Benefits	1) Reliable and non-intermittent renewable source of cooling [9]. 2) Reduce greenhouse gas emissions from cooling processes [43]. 3) Mature technology [9]. 4) Energy and cost savings for base load cooling processes [45]. 5) Reduce electricity peak load during warm days [3]. 6) Reduction of around 80% in electricity consumption [8]. 7) Reduces fuel and water consumption in cooling systems [7]. 8) Cooling costs independent of volatile energy and electricity prices. 9) Reduce heat island phenomenon caused by conventional AC systems [46]. 10) Reduce the need of refrigerant gases [46]. 11) Costs of seawater pipelines, tunnel drilling and blasting reduction due to advances in oil and gas extraction, hydropower and civil engineering.
Challenges	1) The deep seawater outlet should be handled with care to minimize its impact on coastal wildlife [47]. Best practice from power plant cooling and desalination plant water discharge can be applied. 2) The heat losses in the intake pipelines should be minimized [48]. 3) District cooling and buildings retrofit demand high capital costs [7]. 4) Risk of thermal shock and increased nutrient loading in the deep seawater outlet [31]. 5) Cavitation and pipe collapse resulting from water suction with the pump [49, 50]. 6) Detailed knowledge required for project design, such as seawater temperature depth profiles [51]. 7) Detailed knowledge on SWAC cooling demand requirements (including daily and seasonal loading) and prediction of future cooling demand growth. 8) Optimal design of the project, such as pipe diameter, length, seawater pump excavation, thermal energy storage, etc. 9) Cooling demand requirements should be high as possible, which is not always the case before project construction due to the risks involved in the investment.

Table 4: Data input into the SWAC world potential model.

Data	Description	Resolution	Purpose	References	Figure 7 Model Step
NODC (Levitus) World Ocean Atlas	Annual, seasonal, and monthly temperature and salinity data at multiple depths.	1 arc degree	Create dataset and map with the world ocean depth with seawater temperature < 5^{o}C.	[68]	Step 1
General Bathymetric Chart of the Oceans (GEBCO)	Bathymetric data of the world ocean, seas and lakes, and topography of islands and continents.	30 arc seconds	Develop a model to estimate the distance from the coast to ocean and sea depths where the seawater temperature is < 5^{o}C.	[69]	Step2
ERA Interim, Daily Temperature data	Combination of climatological data and meteorological stations across the world's for 4 hourly measurements per day.	0.75 arc degree	Produce world maps with the number of hours from 2008 until 2017 in which the surface air temperature is above a given value.	[70, 71, 72]	Step 3

Table 5: Data based used to estimate the world potential for SWAC.

Model tasks in Figure 7	Step	Data input	Description	Data output
Examine TW at depth 0 to 2500 m	Step 1	Ocean seawater temperature at different depth (NODC), 1 deg. res.	Find the temperature at different depths.	-
Identify depths with TW ≤ 5°C	Step 1	//	Record the depth in which TW* ≤ 5°C.	Ocean depth with TW ≤ 5°C, 1 deg. res.
Find location with TW ≤ 5°C	Step 2	Bathymetry and topography of the world (GEBCO), 30 secs. res.	Look for locations by the coast and with a distance of 1 from ocean depths with TW* ≤ 5°C.	-
Increase pipeline in 1 km up to 30	Step 2	//	Increase the pipeline length from 1 to 30 km when looking for ocean depths with TW* ≤ 5°C from coastal areas around the world.	World SWAC projects with pipeline up to 30 km, 30 secs res. Length of pipeline from coast to TW ≤ 5°C, 2.5 deg. res
Add hours above 20-30°C from 2008-2017	Step 3	Hourly world surface air temperature (ERA), 0.75 deg. res.	Go through surface air temperature from 2008 until 2017 and sum the hours in which the temperature is higher than 20,22,24,26,28,30°C.	Hours with temperature higher than 20,22,24,26,28,30°C
Estimate the SWAC capacity factor	Step 3	Hours with temperature higher than 20,22,24,26,28 ,30°C	Eq. 3 is used to estimate the capacity factor. It assumes a SWAC project, which intends to reduce the ambient temperature from 30 to 20°C.	SWAC capacity factor for cooling from 30 to 20°C
Compare SWAC pipeline length capacity factor and depth	Step 4	SWAC capacity factor for cooling from 30 to 20°C Length of pipeline from coast to TW ≤ 5°C, 2.5 deg. res	The selected projects around the world with the smallest pipeline length in 2.5 deg. res., their capacity factor and seawater intake depth are compared.	SWAC capacity factor of selected projects, 2.5 deg. res. Depth with TW ≤ 5 of selected SWAC projects, 2.5 deg. res. Capacity factor, pipeline length and seawater depth comparison

* Seawater temperature (TW).