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Seawater air-conditioning and ammonia district cooling: A solution for warm coastal regions

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ABSTRACT

The world switching to more sustainable energy sources to curb CO_2 emissions and haul climate change. One sector expected to see rapid growth in energy consumption is the cooling sector due to population growth and climate change. A sustainable solution for cooling needs in coastal areas that are not often addressed is seawater air-conditioning, which pumps cold water from the deep sea to the shore and uses it for cooling. The main challenge for this technology is to distribute the cooling service. This paper proposes using pressurized ammonia to distribute the cooling services provided by SWAC plants. Results show that ammonia district cooling allows SWAC to significantly increase its load demand and lower cooling costs. Ammonia district cooling could be the missing piece for implementing seawater air-conditioning due to its potential to increase the cooling load of district cooling systems.

1. 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 TWh/year in 2000 to 4000 in 2050 and 10,000 by 2100 [1]. Other estimates predict that demand for cooling is set to surpass heating around 2070, as shown in Fig. 1 [2]. 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. Even though district heating is widely disseminated [3–6], district cooling is still in its infancy [7–10].

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 [11], as shown in Fig. 2. The difference in temperature between the surface and deep ocean has been extensively studied for electricity generation and desalination purposes [12–15].

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 [18]. SWAC replaces chillers used in conventional AC systems, significantly reducing the electricity consumption and cooling costs [19,20]. The electricity cost of a SWAC system is usually 80% lower than conventional AC systems [21] and consists of around 20% of SWAC total project costs [22,23]. These cooling demand projects should be as large as possible to reduce the overall costs of the project [22]. This is due to due to economies of scale. A SWAC project requires design, planning, permission, land acquisition, topography screaming and pipeline installation. These costs are similar for small- or large-scale SWAC projects. Also, the circumference of the pipeline, which is proportional to its cost, increases proportionally with the radius of the pipeline. However, the flow area of the pipeline increases to the

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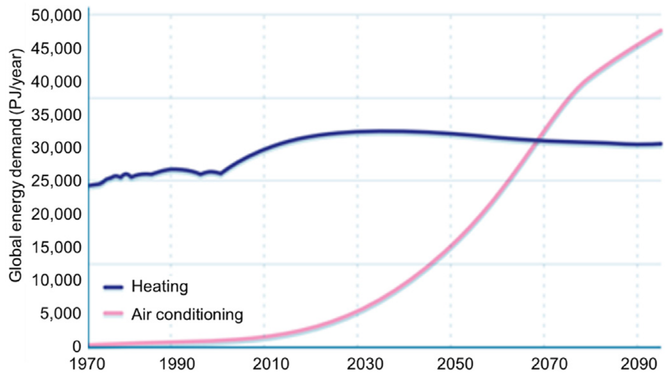

Fig. 1. Projected global demand for heating versus cooling, 1970–2090 [2].

power of two. Friction losses in larger pipes are also smaller.

The use of ammonia as a refrigerant and absorption cooling is rising [24], as it is a cheap refrigerant [25] that follows the Montreal Protocol on Substances that Deplete the Ozone Layer [26] and results in efficient cooling systems [27,28]. Apart from only producing cooling services, an ammonia refrigeration system can be used to provide combined cooling and power [29,30]. Ammonia is also a valuable energy carrier. It carries energy chemically or through gas-liquid phase change [31]. The use of ammonia to distribute cooling is applied in industrial processes. However, to our knowledge, ammonia as a phase change energy carrier in district cooling systems is not yet applied or proposed in the literature.

This paper proposes using an ammonia-based district cooling system to distribute the cooling services provided by SWAC plants more efficiently and at a lower cost. This is the first time the combination of SWAC and ammonia district cooling has been analyzed in the literature. This paper is divided into five main sections. Section 2 presents and explains the methodology applied in this study (ammonia SWAC). Section 3 presents the results of this paper. Section 4 discusses the pros and cons of the proposed technological arrangement. Section 5 concludes the paper.

2. Methodology

This paper proposes a significant design change to the conventional SWAC plant. Fig. 3 presents the configuration of the proposed ammonia SWAC system suggested in this article. The proposed ammonia SWAC system consists of nine main components, and these are: (1) cold seawater inlet, (2) seawater pump, (3) heat exchanger and ammonia condensation, (4) warm seawater outlet, (5) seawater thermal energy storage tank, (6) ammonia thermal energy storage tank, (7) ammonia-based district cooling system, (8) cooling demand, (9) synergy with renewable sources. The main difference between ammonia SWAC, and conventional SWAC is that conventional SWAC uses fresh water to transport the cooling services in the district cooling system. The pumped seawater is used to condense ammonia, and the liquid ammonia is pumped to the end customer, where it evaporates, effectively transferring the cooling service (Fig. 4 (a) and (b)). More details can be seen in Refs. [22,32–35].

Fig. 5 presents the methodological framework of the paper. The methodology is divided into three main steps. Step 1 intends to validate the ammonia SWAC concept. Firstly, it compares steam and ammonia as energy carriers. Secondly, it compares water and ammonia-based district cooling systems and analyses the pros and cons of the system. Step 2 describes the rationale for the proposed district cooling system. Firstly, it analyses the ammonia pressure required to achieve phase change at the temperature provided by the SWAC plant. Secondly, it proposes different arrangements for designing an ammonia SWAC plant. Step 3 estimates the potential for SWAC plants and thermal energy storage with ammonia SWAC. It investigates the impact of cooling demand on the cost of cooling and estimates the global potential for ammonia SWAC plants.

Seawater air conditioning systems are designed to transport the cooling services by pumping cold water to the final customer. The amount of cooling energy transported follows Equation (1).

$$Q = m_w \, c \, \Delta T \quad (1)$$

where, Q is the heat transferred in the district system (in W). m_w is the mass of freshwater pumped in the district system (in kg/s). c is

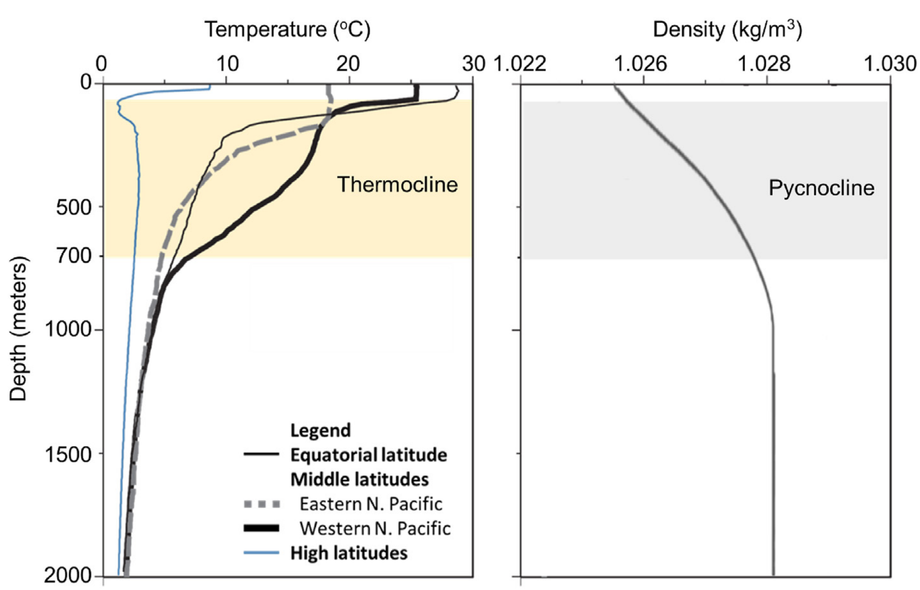

Fig. 2. Typical temperature and density variation with water depth in the open ocean. Adapted from Refs. [16,17].

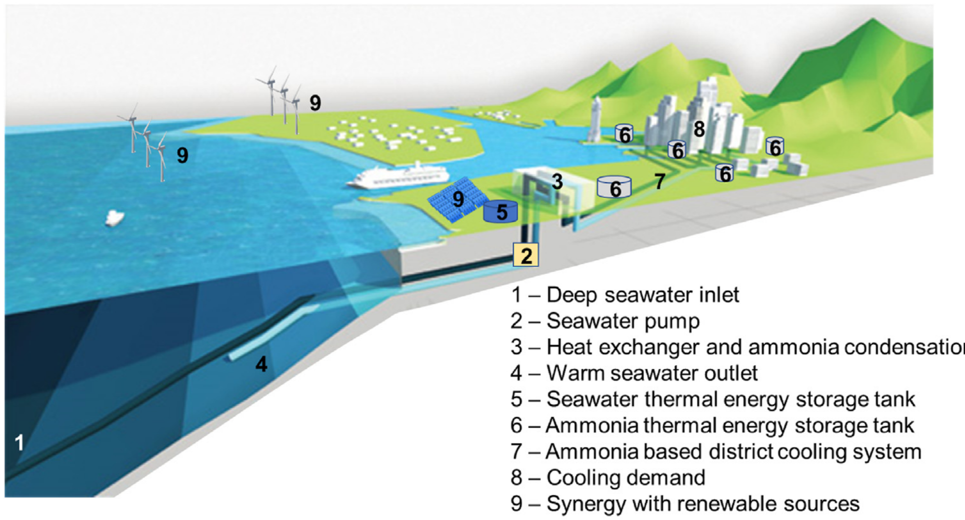

Fig. 3. Ammonia seawater air-conditioning scheme main components. Adapted from Ref. [36].

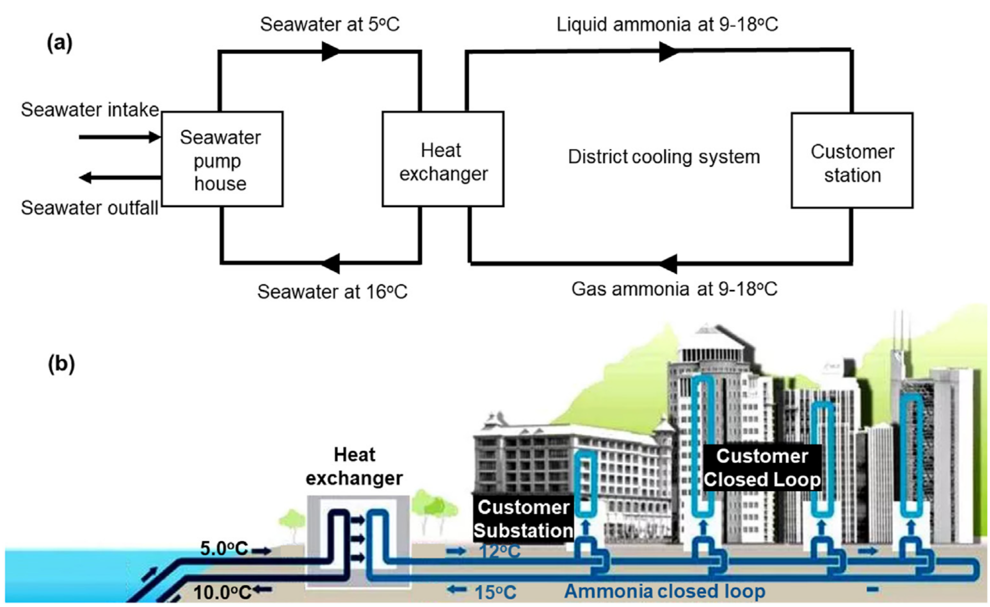

Fig. 4. Seawater air-conditioning (a) process diagram and (b) longitudinal section [37,38].

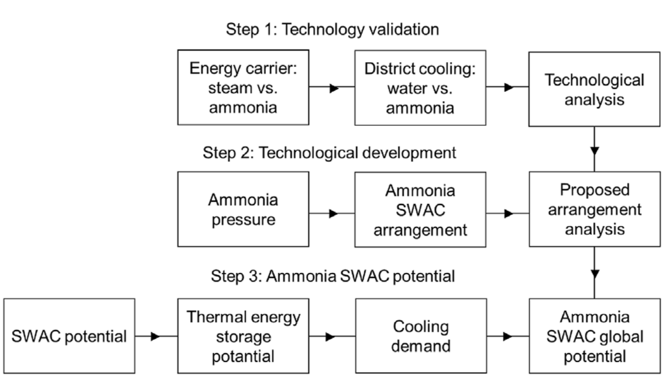

Fig. 5. Methodological framework of the paper.

the specific heat capacity, equal to 4.2 kJ/kg.C, ΔT is the temperature difference of the water between the inlet and outlet in the district cooling system (in ^{o}C), and ranges from 5 to 10 °C.

As proposed in this paper, a more efficient approach to transporting cool is to create a district cooling system with pressurized ammonia.

$$Q = m_a L \tag{2}$$

where, m_a is the mass of ammonia pumped into the district cooling system (in kg/s). L is the latent heat of ammonia vaporization, equal to 1369 kJ/kg.

3. Results

Both steam and ammonia are good phase change energy carriers due to their high latent heat of vaporization. Table 1 compares

Table 1
Comparison between steam and ammonia-based district heating/cooling systems [40,41].

	Steam	Ammonia	Comparison
Latent heat of vaporization (kJ/kg)	2265	1369	60%
Liquid density (kg/m^3)[a]	908	626	69%
Gas density (kg/m^3)[a]	3.2	4.8	150%
Latent heat per gas volume (kJ/m^3)[a]	7248	6571.2	91%
Cost (USD/kg)	–	0.5 [42]	–
Molar mass (g/mol)	18	17	94%
Bolling point at 1 bar (°C)	100	−33.3	–
Bolling point at 6 bar (°C)	159.2	9.3	–
Temperature difference compared to 20 (°C)	139.2	10.7	7.7%
Toxicity	Nontoxic	Toxic	–

[a] Pressure 6 bar and phase change temperature.

steam and ammonia-based district heating/cooling systems. The latent heat of vaporization of steam and ammonia are the highest for gas at standard temperature and pressure, with 2265 and 1369 kJ/kg, respectively. Steam has a boiling point of 100 °C and 159.2 °C at 1 and 6 bar, respectively, and ammonia −33.3 °C and 9.3 °C. This makes steam a good energy carrier for district heating applications and ammonia good for district cooling applications. The bottleneck for constructing a district cooling system is the transport of the gaseous ammonia back to the SWAC plant. Comparing the use of steam and ammonia for heat transportation, steam transports only 9% more energy than ammonia by volume. Another great advantage of using ammonia for district cooling is that the temperature difference between the steam district heating system and the environment is significantly higher than the temperature difference between the steam district heating system and the environment. In other words, ammonia can be argued to be a better option for transporting thermal energy than steam, given the smaller temperature difference compared to the ambient temperature, and thus, the fewer energy losses to the environment and insulation cost required. The main drawback of ammonia is the higher costs and its toxicity [39]. One advantage that significantly facilitates the management of accidents with ammonia is that ammonia is a lighter-than-air gas. As soon as it evaporates, it will rise to higher levels in the atmosphere and dissipate rapidly.

Now that we have shown that ammonia has good potential to be a phase change energy carrier in district cooling systems, we can compare the use of the sensible heat of water versus phase change ammonia in district cooling systems (Table 2). Even though the sensible heat of water is high, the heat transported by weight is small (126 kJ/kg) compared with the latent heat of ammonia (1369 kJ/kg). This would result in around 10 times higher energy consumption for pumping and significantly larger pipelines to transport the water, increasing investment costs. The usual pumping requirements for the water district cooling are estimated at 27 tons of cooling/kWe for small SWAC systems [22]. The pumping requirements for an ammonia-based district cooling system are significantly smaller because of the higher heat transported by weight (1369 kJ/kg) and the pressure reduction with ammonia condensation sucks the ammonia gas to the condenser, without the need of compressors. Another great benefit of ammonia-based SWAC is that the coolant temperature remains the same when it is being delivered to the final customer with an average heat delivery temperature of 10 °C, which is significantly higher than the usual 5 °C in water-based SWAC (Fig. 6). This results in fewer investments required by the end customer. There are also several other benefits of ammonia-based SWAC plants, such as the

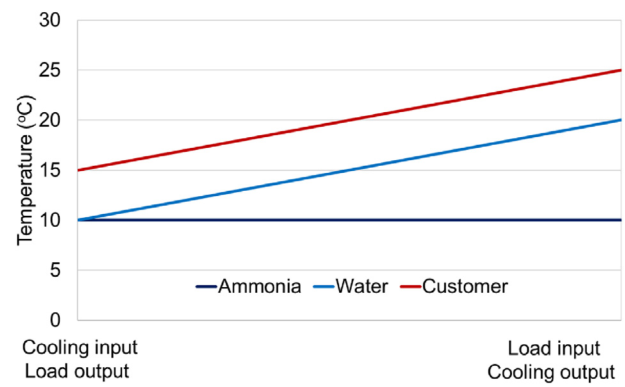

Fig. 6. Comparison between cooling load delivery temperature difference with water and ammonia SWAC.

Table 2
Comparison between water and ammonia SWAC district cooling systems.

	Water	Ammonia	Comparison
Heat transfer media	Sensible heat	Latent heat	–
Sensible heat (J/g.C)	4.2	–	–
Temperature difference (°C)	20	–	–
Heat transported by weight (kJ/kg)	126	1369	1087%
Temperature difference in heat delivery (°C)[a]	5	10	200%
Customer investment requirements	high	low	better
District cooling capital costs	high	low	better
Pumping costs	high	low	better
District cooling distance from SWAC plant	short	long	better
Cooling demand potential	low	high	better
Risk of accidents	low	high	worst
Thermal energy storage seawater tanks	yes	yes	same
Thermal energy storage close to customer	no	yes	better

*Pressure 6 bar and phase change temperature.
[a] Assuming the case presented in Fig. 6.

possibility of reaching longer cooling demand distances and larger cooling demand potentials and storing ammonia close to the end customer to optimize the district cooling system. The only disadvantage is the risks of accidents, which should be carefully analyzed and mitigated due to intoxication with ammonia or explosions.

Fig. 7 shows in phase change temperature and pressure curve for ammonia from 0 °C to 40 °C. The pressures most interested in implementing ammonia SWAC district cooling systems vary from 9.3 °C with a pressure of 6 bar to 17.8 °C with a pressure of 8 bar. In case of emergencies or power cuts, the ammonia district cooling system might gain excess heat, which would result in a rise in pressure of the system. This could be controlled by venting or flaring ammonia from the system to keep the pressure down. In critical sections where venting or flaring is not an option, the system could be designed to withstand an 18 bar pressure to contain the ammonia at a temperature 0f 40 °C and avoid a possible explosion of the system.

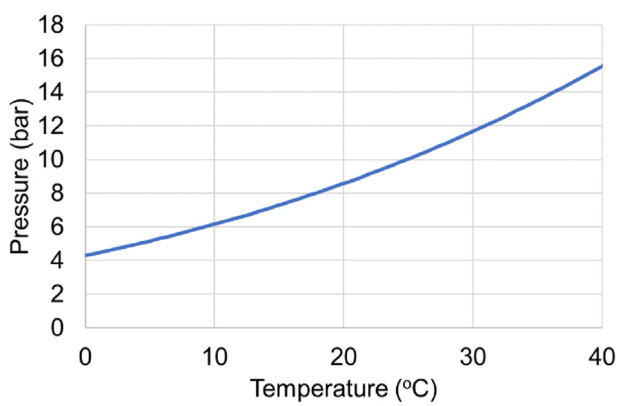

Fig. 7. Phase change temperature and pressure curve for ammonia [43].

Depending on the demand for cooling, the ammonia SWAC system could have one ammonia district cooling system with the same pressure or have several ammonia district cooling systems with different pressures. For example, a one pressure system with boiling pressure of 9 bar and 9.3 °C, would provide low temperature cooling services, but it would only extract 3° of cooling potential from the deep seawater, as shown in Table 3. On the other hand, a system with a pressure of 8 bar and boiling temperature of 17.8 °C would supply cooling at a higher temperature. Still, it would extract 11° of cooling potential from the deep seawater. An option to combine both the possibility of providing low temperature cooling and using the cooling potential from the deep seawater is to create two or more ammonia SWAC district cooling systems operating at different pressures. Apart from increasing the system's efficiency, using the cooling potential from the deep seawater as much as possible also reduces the environmental impact when returning the seawater to the ocean.

To optimize the cooling capacity for the SWAC plant and reduce environmental impact, we propose the arrangement in Table 3 and Fig. 8. This consists of a combination of ammonia pressure systems and a final sensible water-cooling stage to increase the cooling capacity of the SWAC plant. Table 3 presents the possible services related to the different ammonia pressure systems and the water distribution system. The capital investment of such a system increases due to the need for more equipment and the division of the cooling load.

The ammonia district cooling with 6 bar has a lower installation cost than the 8 bar system. However, the 8 bar system has lower operating cost due to the smaller heat losses resulting from the higher temperatures and because the higher pressure results in lower gas velocities and, thus, lower pressure losses in the system. The best system to supply the cooling demand for close and distant customers will depend on the energy costs, interest rates, and several other factors specific to the location where the project will be implemented.

Table 3
Combination of ammonia district cooling pressure systems.

Ammonia pressure (bar)	Boling temperature (°C)	SWAC temperature range (°C)	ΔT (°C)	Services that demand cooling at these temperatures
6	9.3	5–8	3	Food processing industry, chemical industry, ice factories, recreation (artificial ski resorts, ice skating rink, ice bars), supermarkets, liquid energy storage plants.
7	13.8	8–12	4	High quality cooling demand in hotels, resorts, offices, cinemas, and shopping centers.
8	17.8	12–16	4	Space cooling (residential, public building, commercial)
Water	–	16–25	9	Cooling demands close to the SWAC plant (airport, supermarket, shopping centers), fish and crustacean production, parks, urban cooling, recreation (chilled pools), greenhouse production of vegetables and fruits.
Total			20	

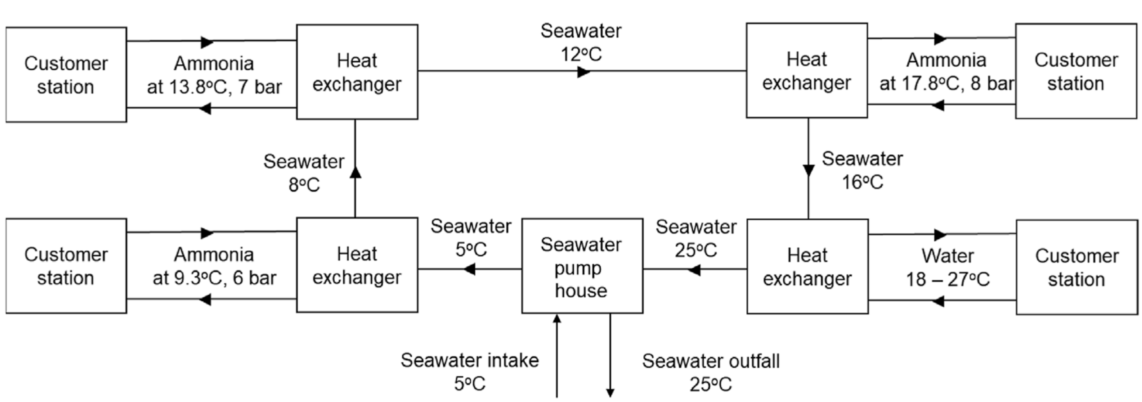

Fig. 8. Proposed arrangement for SWAC ammonia-based district cooling.

To illustrate the substantial potential of SWAC, Table 4 and Fig. 9 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 20 °C temperature change is equivalent to a hydropower plant with a generation head of 18,6 m and 200 times the flow or equivalent to a 976,000 m^2 solar power plant, or equivalent to 42 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 (unit of cold created per unit of electricity consumed) is around 15 [6], whereas for high efficient conventional coolers, COP is 4.

Another benefit of ammonia SWAC is the possibility of storing thermal energy in seawater and liquified ammonia (Fig. 10). The seawater tank stores seawater before it passes through the heat exchanger. This is particularly interesting to allow the seawater pipeline to operate at full capacity during the day and night or weekly cycles, increasing the viability of the plant. A tank with 1000 m^3 seawater storage capacity has the potential of storing up to 23 MWht, assuming a temperature difference usage of 20 °C. This is equivalent to the storage capacity of 18 electric trucks, assuming a storage capacity of 500 kWhe and a refrigeration COP of 2.5. This is competitive with other energy storage technologies [44–53]. The liquid ammonia tank store cooling energy close to the end customer to improve the efficiency of the district cooling system and describes it as follows.

Another interesting approach for storing ammonia in a district cooling plant is presented in Fig. 11. The share of liquid and gas ammonia in the refrigeration system must always be the same

Table 4
Comparison of deep ocean seawater with other cooling sources.

Source of Energy	Driving Force	Quantity	Electricity Generation/Consumption	Cooling Potential
Deep Seawater	Temperature Difference: $\Delta T = 20$ °C	Deep Seawater Flow: 1 m^3/s	-2 MW_e[a]	20 °C × 4.0 kJ/kg.K[b] x 1 m^3/s x 1028 kg/m^{3iv} = 82 MW_t[d]
Hydropower	Height: ΔH = 18.6 m at 90% efficiency	Dam Turbine Flow: 200 m^3/s	18.6 m × 9.8 m^3/s x 20 m^3/s x 0.9 = 32.8 MW_e	32.8 MW_e x 2.5[e] (COP) = 82 MW_t
Photovoltaic Cells	Solar Irradiation: 0.24 kW_e/m^2 at 14% capacity factor	Photovoltaic Cells: Area 976,000 m^2	0.24 kW_e/m^2 x 976,000 m^2 x 0.14 = 32.8 MW_e	32.8 MW_e x 2.5[c] (COP) = 82 MW_t
Wind Power	Wind Generation: 2 MW_e at 40% capacity factor	Number of wind turbines: 42 turbines	2 MW_e × 0.4 × 42 = 32.8 MW_e	32.8 MW_e x 2.5[c] (COP) = 82 MW_t

[i] Assuming the energy for seawater pump and district cooling system [6].
[a] Megawatts of electricity.
[b] The density of seawater at 5 °C and with 35 g of salt/kg of water is 1028 kg/m^3 [2].
[c] The specific heat of seawater at 0 °C with 35 g of salt/kg of water is 3.985 kJ/kg.K [2].
[d] Megawatts of thermal energy for cooling.
[e] Assuming that electricity conversion to cooling power has a coefficient of performance (COP) of 2.5. The COP of 2.5 is relatively conservative by modern efficiency standards.

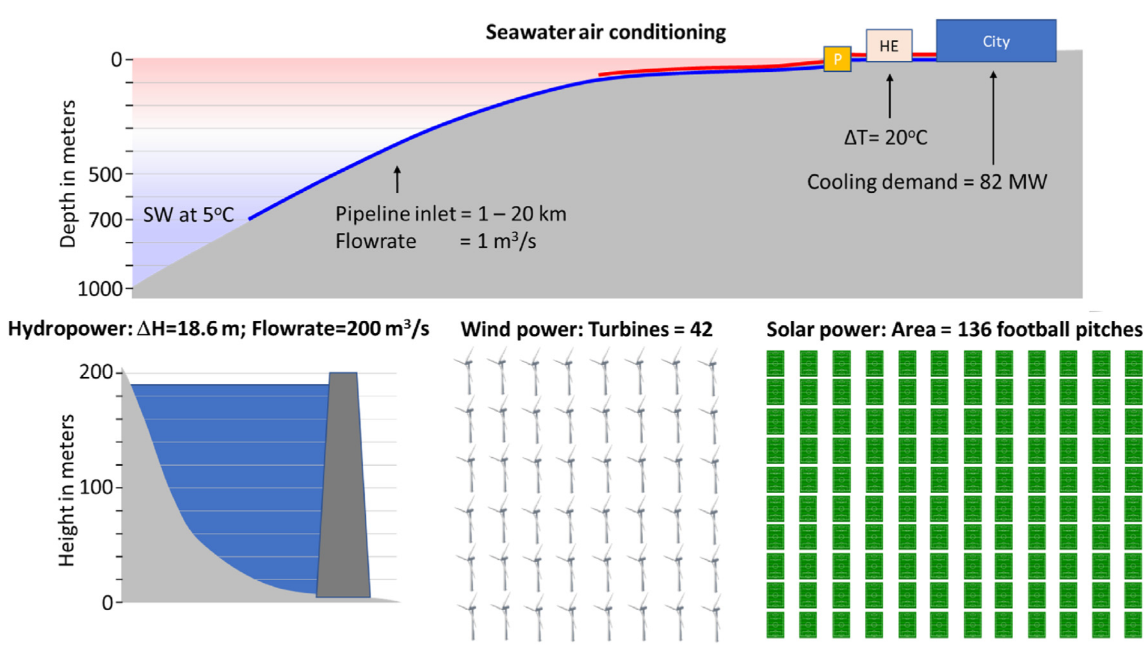

Fig. 9. SWAC cooling load potential compared with other renewable sources.

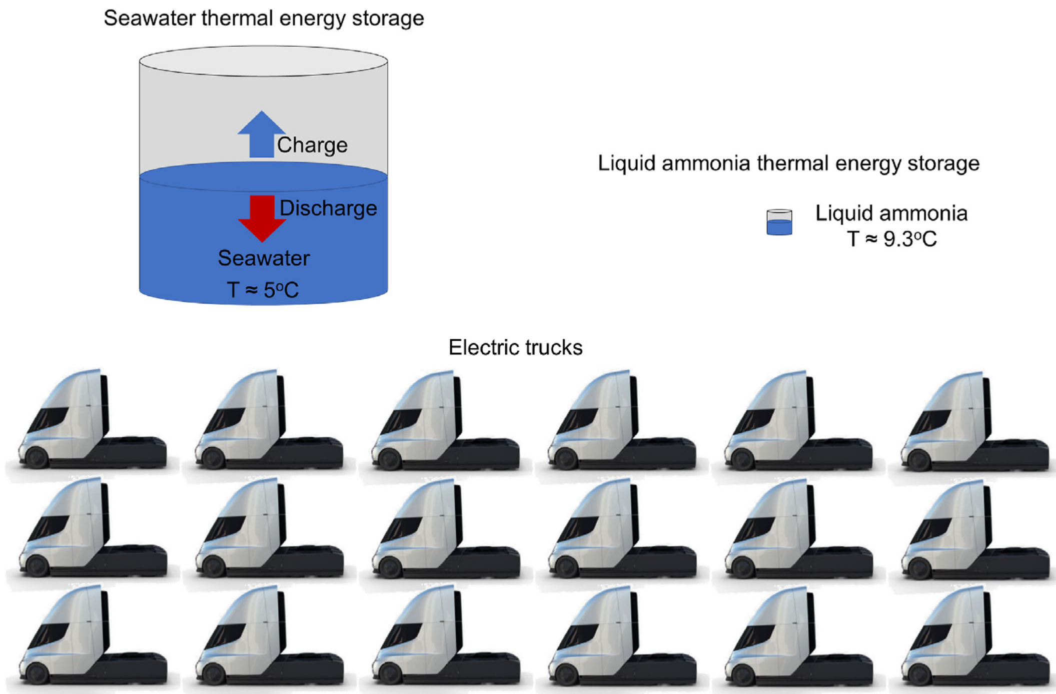

Fig. 10. Comparison of the thermal energy stored in a 1000 m^3 seawater thermal energy storage tank, 98 m^3 of liquid ammonia energy storage tank, and 18 electric trucks (maintaining the same size proportion between the technologies).

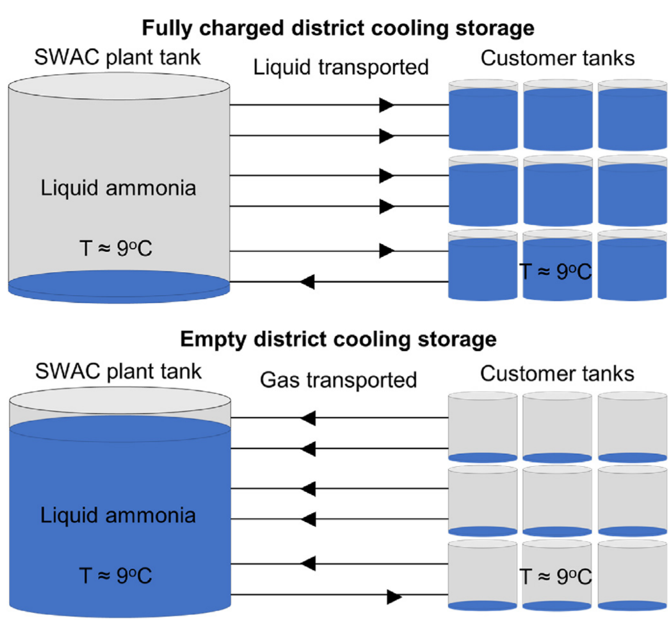

Fig. 11. Proposed arrangement for SWAC ammonia-based district cooling.

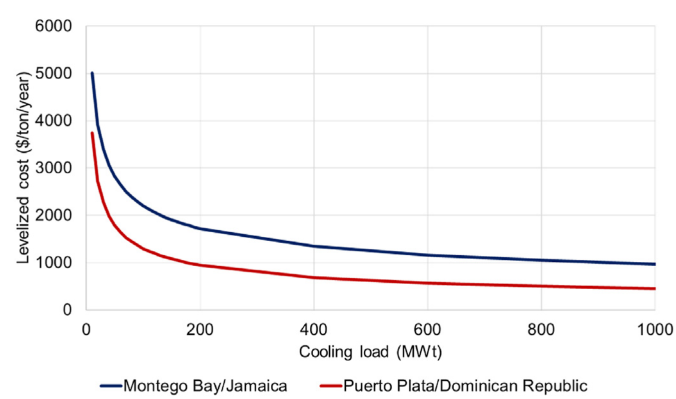

Fig. 12. Change in cost with cooling demand [22].

percentage to avoid the system building up pressure and exploding or lowering its pressure and collapse. Thus, the storage of ammonia close to the final customer must be compensated by another liquid ammonia storage tank in the SWAC plant. The advantage of this system is that during periods when the demand for cooling is low, during the night, most district cooling pipelines in the system are used to pump liquid ammonia from the SWAC plant tank to the customer tanks, only a small fraction of the pipeline will be used to transport ammonia gas back to the SWAC plant, due to the cooling existing cooling load at night. During periods with high cooling demand, during the daytime, most pipelines in the district cooling system will be used to transport ammonia gas back to the SWAC plant, and only a few pipelines will be used to supply additional liquid ammonia to the customers. This arrangement significantly improves the system's operation by giving more flexibility for the district system to operate as efficiently as possible. If the storage capacity on both sides of the district cooling system is large enough, it can double its cooling capacity with the existing infrastructure.

Fig. 12 presents an extrapolation of the change in costs for SWAC for cooling in Montego Bay in Jamaica ($11396x^{-0.357}$) and Puerto Plata in the Dominican Republic ($10806x^{-0.46}$), where ‘x’ is the cooling load in MWt. Compared to the costs of air-conditioning in Montego Bay of 5200 $/ton/year and Puerto Plata of 4700 $/ton/year, A SWAC project to supply a cooling load of 1000 MWt, costs 5 times lower in Montego Bay and 10 times lower in Puerto Plata [22]. However, achieving this low cost is only possible with a viable and practical solution to distribute the cooling service to locations 5–10 km around the SWAC plant. To supply a cooling load of

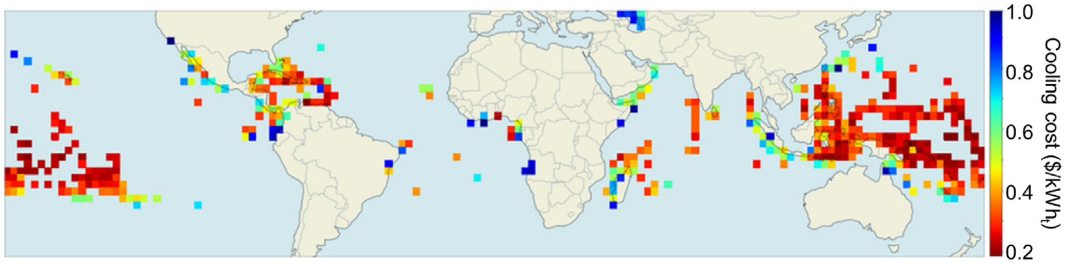

Fig. 13. Global cost estimate for seawater air conditioning [54].

1000 MWt, assuming the inlet temperature is 5 °C and the outlet temperature is 25 °C, 30% of the cooling energy is lost. To supply this cooling demand, the flow of seawater required is 17 m^3/s. To put into perspective, the water consumption of Los Angeles, USA, a city with around 4.000.000 people, is on average 25 m^3/s.

The global potential for SWAC depends on four main parameters (distance to the deep sea, depth to reach 3 °C seawater, and the capacity factor of the SWAC plant). The first three parameters have been considered in Ref. [54] and result in Fig. 13. The cooling demand has already been explored in Ref. [14]. Combining the four parameters results in Table 5, which presents the large global cities with low SWAC cost for cooling, assuming a cooling demand of 24 MWt. This cooling cost can reduce up to 10 times if the cooling demand is 1000 MWt.

Table 5
Large cities with low SWAC cost for cooling, assuming a 24 MWt cooling demand [54].

City/Country	Cooling cost ($/kWh$_t$)
Honolulu/USA	0.3
Havana/Cuba	0.3
San Juan/Porto Rico	0.3
Dominican Republic	0.3
Saint Pierre/Reunion Island	0.3
Male/Maldives	0.3
Ilheus/Brazil	0.4
Puerto Escondido/Mexico	0.7
Recife/Brazil	0.7
Port Moresby/Papua New Guinee	0.7
Puerto Gentil/Gabon	0.8
Salvador/Brazil	0.9
Abidjan/Ivory Coast	0.9
San Diego/USA	1.0

4. Discussion

Table 6 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 Refs. [55,56].

Possible customers with high cooling demands to connect to district cooling systems are airports [62], data centers [63,64], hotels [35], resorts [34], governmental and military facilities, universities [57], large offices and commercial buildings [65,66], shopping malls [67,68], department stores [69], museums [70], residential districts, industrial processes [57], entertainment facilities [71], artificial ski resorts [72,73], temperate fruits and vegetables farming, food and grains storage [74] and so on. SWAC also reduces heat islands due to air conditioning [75]. A detailed worldwide cost estimate for SWAC can be seen in Ref. [54].

District cooling solutions are not only advantageous in coastal regions, where the coast is close to the deep sea. In areas far from the coast, the temperature tends to have large fluctuations between the day and the night. For example, during the day, the temperature could be 35 °C and during the night 20 °C. A district cooling system can use electricity at night and produce cold with a higher coefficient of performance (COP) and store this cooling energy in a thermal energy storage tank so that it is used during the day to liquefy ammonia and operate the district cooling system.

Table 6
Review of benefits and challenges of SWAC.

Benefits	1) Reliable and non-intermittent renewable source of cooling [35].
	2) Reduce greenhouse gas emissions from cooling processes [56].
	3) Mature technology [35].
	4) Energy and cost savings for baseload cooling processes [57].
	5) Reduce electricity peak load during warm days [34].
	6) Reduction of around 80% in electricity consumption [33].
	7) Reduces fuel and water consumption in cooling systems [22].
	8) Cooling costs independent of volatile energy and electricity prices.
	9) Reduce the heat island phenomenon caused by conventional AC systems [58].
	10) Reduce the need for refrigerant gases [58].
	11) Costs reduction of seawater pipelines, tunnel drilling and blasting due to advances in oil and gas extraction, hydropower and civil engineering.
Challenges	1) High investment costs [22].
	2) The deep seawater outlet should be handled with care to minimize its impact on coastal wildlife [59]. Best practices from power plant cooling and desalination plant water discharge can be applied.
	3) The heat losses in the intake pipelines should be minimized [60].
	4) District cooling and building retrofit demand high capital costs [22].
	5) Risk of thermal shock and increased nutrient loading in the deep seawater outlet [61].
	6) Cavitation and pipe collapse resulting from water suction with the pump [22].
	7) Detailed knowledge required for project design, such as seawater temperature depth profiles [11].
	8) Detailed knowledge of SWAC cooling demand requirements (including daily and seasonal loading) and prediction of future cooling demand growth.
	9) Optimal design of the project, such as pipe diameter, length, seawater pump excavation, thermal energy storage, etc.
	10) 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.

Another approach to transport the cooling potential from a SWAC plant in a decentralized fashion is to freeze water and transport the ice to the delivered location. However, this would only be an interesting alternative in locations with high demand for energy storage, for example, in islands that rely largely on solar power generation. This is because the ice production plant would reduce the water temperature from 10 to 0 °C, while air conditioners would reduce the air temperature from 30 to 20 °C. Both processes have a similar coefficient of performance. The advantage of ice making is that the excess solar generation during the day can be stored in ice to use the cooling service during the night.

5. Conclusion

Even though the authors have not found any paper in the literature or real-life examples of ammonia-based district cooling systems, this paper has shown that ammonia is an exceptional phase change thermal energy carrier to be applied in district cooling systems around the world. Compared to the use of steam in district heating systems, ammonia is more interesting because it has a similar latent heat per gas volume (90% of steam). Still, at the same time, the temperature difference between ammonia and the ambient temperature is significantly smaller than steam (7.7%), which results in fewer energy losses. Compared to water SWAC, ammonia SWAC does not require energy for pumping and requires smaller heat exchangers both on the SWAC plant side and on the customer side. A SWAC plant with a 1 m^3/s flow is equivalent to regenerating the thermal equivalent energy of 42 wind turbines with 2 MW each and 138 football-sized solar PV power plants. Regarding thermal energy storage, a seawater tank with 1000 m^3 can store the same thermal equivalent energy as 18 electric trucks. Several large cities worldwide have shown potential for ammonia SWAC, particularly due to their high cooling load demand, which exceeds 1000 MWt. The paper proposed different arrangements of ammonia SWAC with one or more ammonia pressure systems. The increase in the number of ammonia pressure systems lowers the temperature of the ammonia delivered but increases the investment cost of the system. It also proposes the storage of ammonia close to the end customer to increase the operational efficiency of the ammonia-based district cooling system. Ammonia is the missing link necessary to turn seawater air-conditioning and other district cooling solutions into reality.

Author contributions

Conceptualization, J.H.; methodology, B.Z., A.N; formal analysis, A.N.; investigation, A.N.; data curation, L.C.; writing—original draft preparation, J.H.; writing—review and editing, B.Z.; visualization, J.H.; project administration, P.B.; funding acquisition, A.N.; resources, L.C. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

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