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Design of a Novel CSP/MED Desalination System

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Abstract. We describe the design of a large-scale thermal desalination demonstrator unit for use in arid locations with a medium-to-high DNI. Most of thermal energy is provided by a conventional parabolic trough field, in the case of the demonstrator this being 4MWt. The desalination sub-system comprises a 3-effect MED, the first stage of which is a large 20 m diameter glass and steel-structured geodesic and transparent dome. The thermal energy is supplemented by direct sunlight transmitted through the dome and by an arc of small heliostats which focus yet more sunlight onto the dome itself. The prototype is under construction at Neom in KSA.

ABBREVIATIONS

DNI – Direct normal irradiance
MED – Multi-effect distillation
KSA – Kingdom of Saudi Arabia
CSP – Concentrating solar power
HTF – Heat transfer fluid
TMY – Typical meteorological year
SCA – Solar collector array
RO – Reverse Osmosis
ppm – parts per million (number of units of mass of a contaminant per million units of total mass)

INTRODUCTION

Solar-powered desalination, the theory and practice, has been under development since the start of the 21st century. But the challenge has been around gaining hard evidence of viability in terms of costs and scale: a leap into large-scale investment has been needed before the concept could be fully proven.

Finally the breakthrough has come in 2020 with the development of technologies for Neom, the $500 billion mega-city under development in Saudi Arabia [1]. Part of the future vision of His Royal Highness Crown Prince Mohammed Bin Salman to diversify the country's economy towards tourism and entertainment, Neom is due to be 33 times the size of New York and planned as a living lab for futuristic urban technologies such as flying vehicles, robot workers and the city's own artificial moon. The city is being sited in 10,000 square miles of the desert Tabuk Province close to the Red Sea.

Such a vast and concentrated human population needs water supplies at a scale that can only be provided by a combination of technologies. One of these is due to be 'cloud seeding' to encourage artificial clouds and rainfall, alongside an 'Internet of Water' to focus on efficiency and sustainability in how water is used in domestic, business and industrial locations. Desalination of seawater from the Red Sea is to be a major source of supplies, including demonstrating technology from the UK's Solar Water plc, solar enhanced green-houses co-developed and refined by Cranfield University.

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Desalination plants - converting seawater into drinking water and water for agriculture - have been used since the 1950s in the Middle East and tropical regions of the world. But while the technology has met urgent needs for clean water supplies, the environmental cost has been heavy, dependent on oil and gas-powered plants. It's been estimated, for example, that the thirty desalination plants in Saudi Arabia rely on around 300,000 barrels of crude oil each day [2]. The World Bank has said it is "critical" that the desalination industry makes the shift away from fossil fuels. More than the fuels involved there are also the environmental risks presented by the large-scale traffic in oil tankers. The majority of conventional desalination plants also dispose of the collected brine form the process back into oceans, causing damage to marine ecosystems.

The current output of desalination plants globally is more than 70 million cubic metres per day, and growing populations and their demands for higher standards of living mean this figure will need to grow exponentially to meet needs - and wants. In the Middle East and North Africa the gap between demand for water and actual supply is said to be around 42 cubic kilometres per year, according to the World Bank figures [3], and expected to increase by five times that by 2050.The problem is shared by other desert regions like Australia and parts of the USA - as well as regions where there's rainfall but the water supply can be contaminated like in India and South America.

DESALINATION SYSTEM CONCEPT

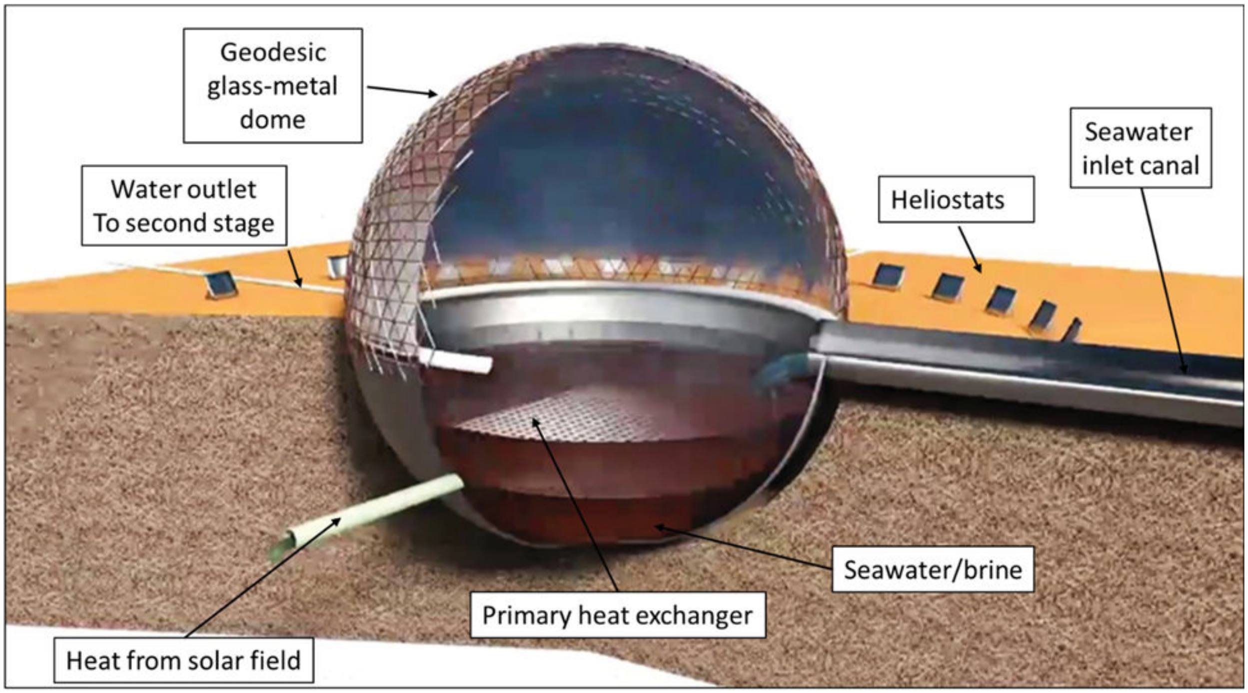


FIGURE 1. Basic concept for the MED desalination dome showing 1st Effect only - main CSP field also not shown.

In collaboration with the UK Company Solar Water plc [4], Cranfield has continued to develop thermal desalination systems. Previously we described small-scale desalination units for use in emergency response situations such as droughts and earthquakes and in refugee camps [5].

Large scale desalination plants present significant challenges [6]. Current state-of-the-art large installations predominantly use Reverse Osmosis (RO) technology. This is a physical process in which the salt is separated from the liquid water using a semi-permeable membrane. By applying pressure in excess of the natural osmotic pressure the membrane will preferentially allow the water molecules to pass through the membrane and a high percentage of the salt and dissolved organic materials will be rejected. Large amounts of power are required to pump the seawater through the membranes and the membranes themselves require cleaning or replacement at regular intervals. RO plants have been successfully built to desalinate such waters as the Red Sea (42,000 ppm) and the Arabian Gulf (50,000 ppm). Current plants burn fossil fuels (mostly oil) and are expensive to build and maintain.

The alternative technology, including the concept described here, is simply to evaporate seawater and distill it in two separate, but connected, processes. This also requires considerable amounts of energy, since it requires over 2300 kJ of heat just to evaporate 1 litre of seawater, before powering the condensation processes. However, renewable energy from solar thermal (CSP) can provide low-cost heat in the solar belt. This provides an opportunity to compete with RO in regions with the highest DNI. These systems include MED (multi-effect distillation) technology. In a classic MED process the incoming seawater is heated to boiling point in the first effect at a pressure of around 8 bar. The water vapour from the first effect condenses in the heating tubes of the second effect. The heat released by the latent heat of condensation evaporates water in the second effect. Often 3 to 5 effects are used. Pressure and boiling temperature decreases with each effect. Heat is only required for the first effect and cooling water only for the final effect. Thus, latent heat is re-used and cooling water requirements are reduced [6].

This latest work with Solar Water plc describes the modelling and design of a large 3-effect MED system to produce up to 1 million liters of clean water per day. The latest concept is shown schematically in Fig.1 above. The first effect of the MED is unusual, comprising a large glass and steel geodesic dome. The thermal energy is provided by a standard parabolic trough CSP field (not shown), supplemented by an arc of heliostats which surround the dome, and further boosted by direct insolation into the dome. Thereafter the system resembles a standard MED system, with the recovery and re-use of latent heat to pre-heat the next batch of incoming seawater.

DESALINATION SYSTEM DESIGN

The overall design concept was provided by Solar Water plc, which included the requirement for a CSP – MED system with a large glass/metal geodesic dome as the first effect, partially surrounded by heliostats to irradiate the dome. It became clear that an adjacent CSP field was required to provide the majority of the thermal energy required to evaporate meaningful volumes of seawater, with the heliostat arc supplementing that input. This is the concept that moved forward to the detailed modelling stage. The desalination system performance was modelled to extract performance data that was then used in an iterative process to optimize the design of the sub-systems and assist in materials specifications and component selection. The basis of the process simulation model is shown in Fig. 2 below. The solar field consists of CSP parabolic troughs which concentrate the solar power onto the working fluid (HTF – thermal oil). The working fluid is heated to a temperature of 130 C in the solar field. After reaching 130 C, the oil is pumped to the desalination dome via a novel heat exchanger serving the base of the dome. Additional solar radiation from the heliostat field impinges directly on the dome. The desalination system consists of three effects. Multiple effects are vital to use the energy efficiently in order to maximize the fresh water production. The solar glass dome forms the first effect; the latter two effects being process vessels. The oil from the solar field is pumped into a heat exchanger located in the water trough below the solar dome. The thermal energy causes the pure water to evaporate thus producing steam, leaving concentrated seawater (brine) behind. This steam will pass into the next stage as shown in the process flow diagram (Fig 2). In the diagram, soldome refers to the glass dome and B3 is the heat exchanger in the dome. Night-time operation would be possible by the addition of thermal storage and a corresponding oversizing of the solar field, but is not considered further in this analysis. The potable water throughput dictates the thermal energy required to service the MED system (with the dome as the first effect). The thermal energy is of the order of 30 MWh for a typical operating day, requiring a solar field of approximately 4MW_{th}.

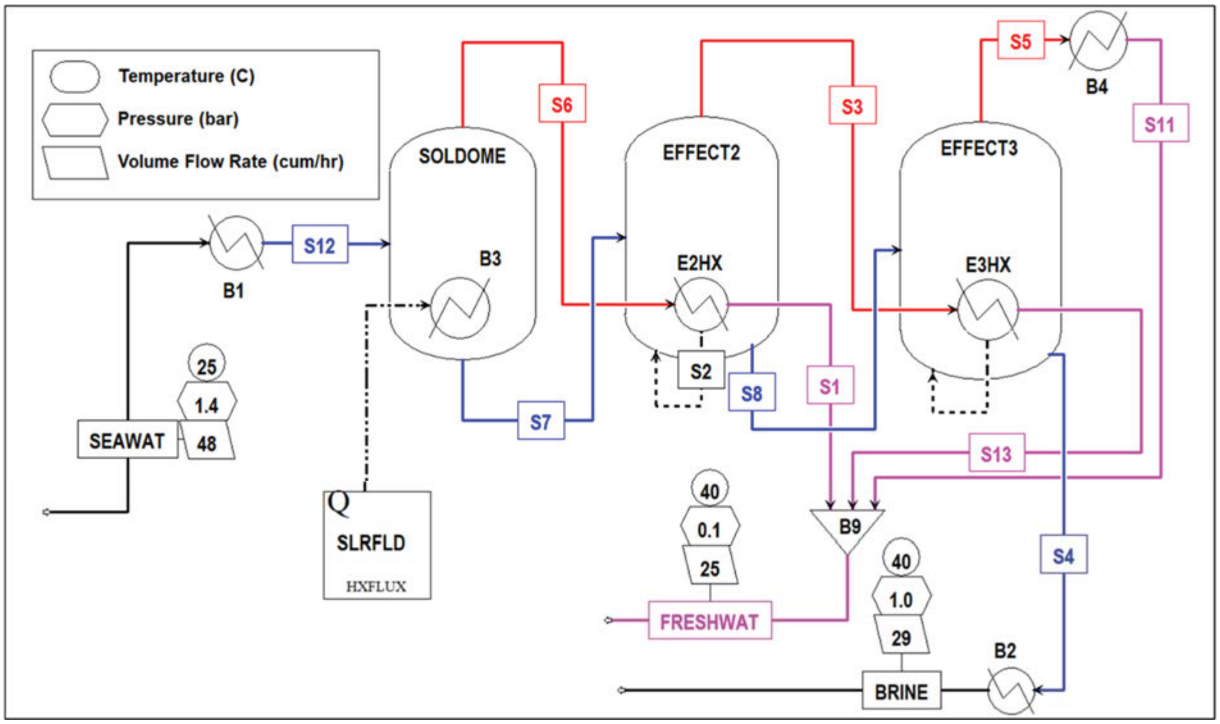


FIGURE 2. Flow schematic of evaporator/condenser sub-stages

SOLAR WATER DOME DESIGN

The solar desalination dome is of geodesic design. Geodesic dome geometry is constructed out of an icosahedron with the 18 triangles which compose the shape split into smaller triangles. But geodesic dome geometry can also be said to be constructed out of pentagons and hexagons. The top of the dome is a pentagon and the joining shapes are hexagons. Figure 3 below shows a construction map of a 6V geodesic dome. On the left is a construction map of the whole dome labelled with members A to I. On the right is the construction map for how each triangle of the icosahedron is split up in a 6V geodesic dome. The two materials considered for the dome structure were steel and aluminium. Steel, although adding weight to the structure, was the preferred option owing to its greater tensile strength.

For the glass which completes the dome structure we proposed 2x low-iron float glass for highest solar factor (g-value) with optional 1x LOW-E coating in order to optimize the heat transfer coefficient (u-value), with all glass thermally toughened for optimal thermal shock resistance

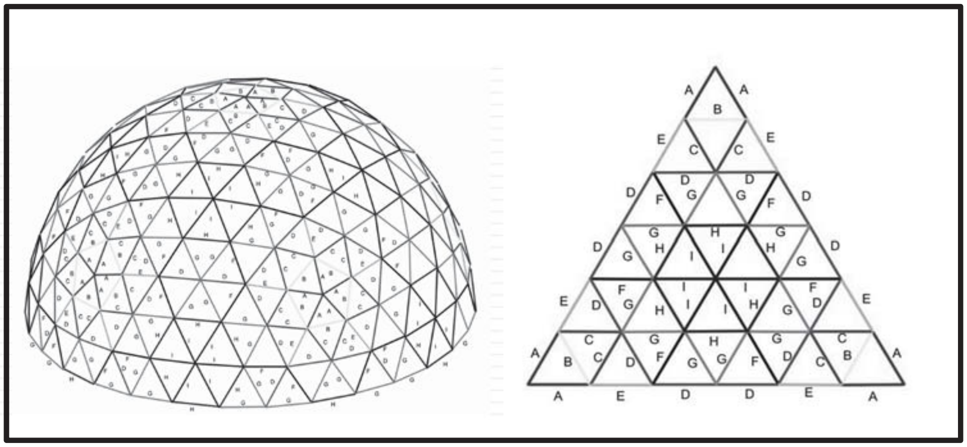


FIGURE 3. 6V Geodesic dome construction map

THERMAL INTERFACES

Two of the most critical design features of the system involve the transfer of heat from the solar field to the seawater in the basin of the dome and the transfer of steam from the dome and into the 2nd effect of the MED system. Fig. 4 below shows the basic design features of each of these. The sea-water basin will have a water input of 48 m^3/h. In order to handle this inflow, the basin is designed to have a residence time of 3 h. Thus the water basin capacity is chosen to be 150m^3. This can be achieved by keeping the basin length, breadth and depth as 10 m, 10 m, and 1.5m respectively. The basin transfer heat exchanger overall parameters were designed using Aspen Plus Model. A heat exchanger area of 18.8 m^2 is required to transfer the required thermal energy. In order to keep the oil flow velocity at 2 m/s [7], a heat exchanger pipe of 150 mm inner diameter is chosen. Based on an approximate heat transfer coefficient, it is estimated that the pipe length is 50 m. The sea water basin dimensions must be taken into account to design the heat exchanger pipe geometry. The heat exchanger pipes will be arranged in the sea water basin as shown in Fig. 4 (left image).

The dome structure serves as the first effect of the triple effect desalination system. Steam from the solar dome passes into the second effect. There are two options for steam exit from the solar dome. In the preferred option (Fig 4 right image), steam is extracted from the solar dome from a centrally placed pipe within the dome structure. The pipework will cross the dome structure underground as shown in the schematic. The advantage of this option is that the glass structure of the solar dome is not altered for accommodating the pipe work. But this option does require a careful design of the pipework to permit the steam exit as the exit pipes will be in a direction opposite to the natural convection direction of steam. A second option was considered which featured a steam extraction pipe at the top of the dome structure following the natural direction of the steam movement. The disadvantage of this option is that provision would have to made to break the dome and extract steam from the top, and this option was abandoned.

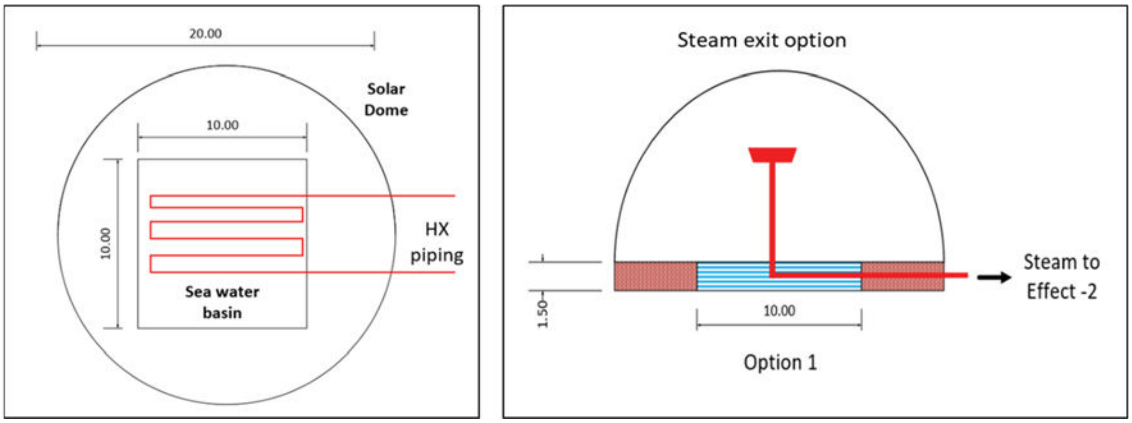


FIGURE 4. Principal heat exchanger (left) and steam exit conduit (right)

SOLAR FIELD AND HELIOSTAT ARC DESIGN

Climate Data

At the Neom location, for a TMY based on the years 2005-2017, the total DNI is 2167 kWh/m^2/yr. The average daily energy received from DNI is 5.9 kWh/m^2/day, with a relatively small variation across the year ranging from 5.1 kWh/m2/day in September to 6.8 kWh/m^2/day in March. There is a significant and consistent difference between the wind speed during the day and during the night. During the night there is a consistent wind speed of between 2 m/s and 3 m/s throughout the year. However, during the day there is a peak in wind in the early afternoon, which ranges from 5 m/s in December to 8.4 m/s in June. The wind predominantly comes from two directions, the North-West and the North-North-East. The lower wind speeds usually come from the NNE direction with the higher wind speeds from the NW. The total number of days that are affected by dust activity is 104 days per year. Dust activity is highest during the spring (February-April). The yearly average temperature is 26.1 C, ranging from a minimum of 13.6 C in October to a maximum of 42 C in September. The average temperature varies between 20 and 30 C, the minimum temperature stays around 15 C and the maximum varies from 27 to 42 C. The yearly average relative humidity is 65%. The minimum humidity is around 20% and the maximum humidity is up to 100%. There is little change in the average humidity throughout the year, ranging from 56% in March to 77% in September.

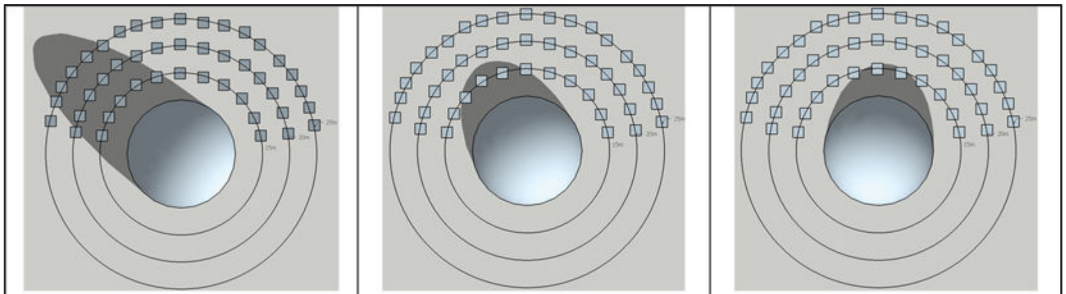
For the design of the desalination installation, especially the large glass/metal dome which constitutes the first effect of the MED system, the primary climate data of interest includes DNI and dust activity. DNI feeds into the design of the CSP field, the heliostat field, and the direct irradiance of the dome. These all feed directly into the calculations of water throughout. The dust in the air is already factored into DNI, but the soiling of CSP mirrors and heliostats, as well as the dome itself, adds cleaning costs to the routine maintenance schedule.

Heliostat Arc

The heliostats are to be placed at the northern side of the dome to reflect additional sunlight into the dome itself. The main heating target within the dome is the water itself, which is at ground level. This makes it difficult to place effective heliostats, as they are normally used to concentrate light at the top of a tower that would be much taller than the current dome. The first limitation is that only two rows of heliostats will be possible without causing extensive blocking of the reflected light from outer rows. The light from the heliostats is concentrated onto a single thermal conducting target, attached to the steam exit pipe placed in the centre of the dome, transferring heat to the seawater in the basin. Each heliostat will be 6 x 4m in size.

The radius of the heliostat arc depends on the shadowing of the heliostats caused by the dome. The sun is lowest in the sky and therefore produces the longest dome shadow during the morning and evening in December. If the heliostats are intended to be used during the whole year to their fullest, then they should be located so that there is no shadow cast by the dome during the day in December. However, for space efficiency we allowed shading of the heliostats during some of the year so that they can be placed closer to the dome. The dome is designed to operate for 8 hours per day, from approximately 9am to 5pm, so it is between these hours that the shading is most important.

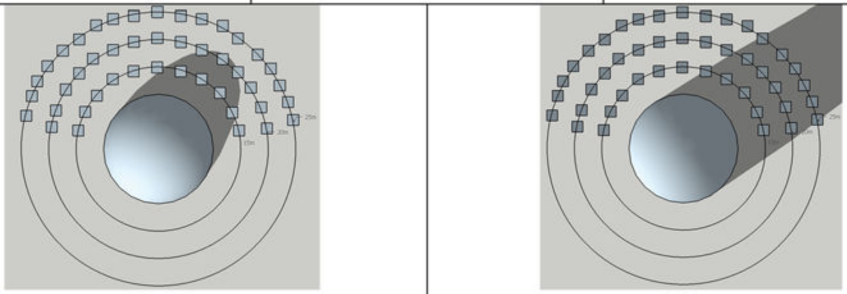
We considered three possible radii for the heliostat field – 15 m, 20 m, and 25 m, along with the shadow cast by the dome for December 21st at 9am, 11am, 1pm, 3pm and 5pm. It can be seen in Fig 5. that there is significant shading for the 15 m radius throughout almost the entire day, with some shading of the 20 m radius during the morning and afternoon. At the earliest and latest part of the day there is shading across all radii, which is unavoidable. Figure 6 shows the shadowing during September 21st, when the solar angles are much higher and there is less effect on the heliostats. In this case, the only shading of the 15 m radius are the early and late part of the day. The same solar angles apply to March 21st, with all days between having higher solar angles. This implies that the days between 21st March and 21st September will have even less shadowing effect on the heliostats and so the 15 m radius would be suitable. In the final design two rows were used with 7 heliostats at 10m and 6 heliostats at 15m. The first row was evenly spaced in a 180 degree arc centred at North. The second row was then evenly spaced in the gaps, ensuring minimal blocking by the first row. The heliostats are provided by SAT Control in Slovenia [8].



9am December 21st

11am December 21st

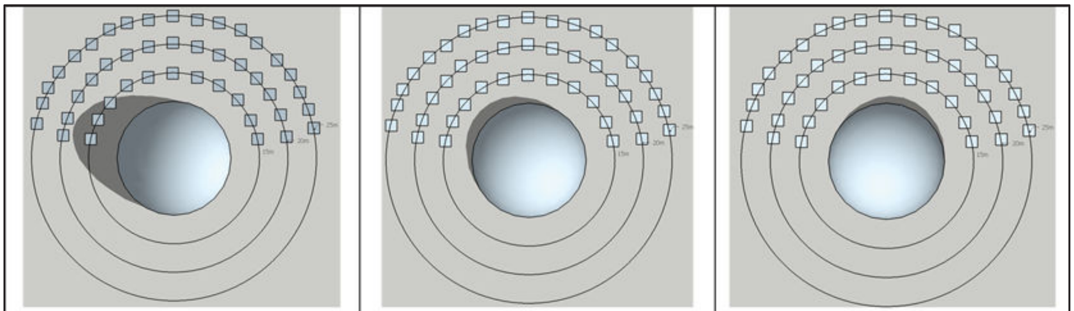
1pm December 21st



3pm December 21st

5pm December 21st

FIGURE 5. Dome shadowing for December 21st



9am September 21st

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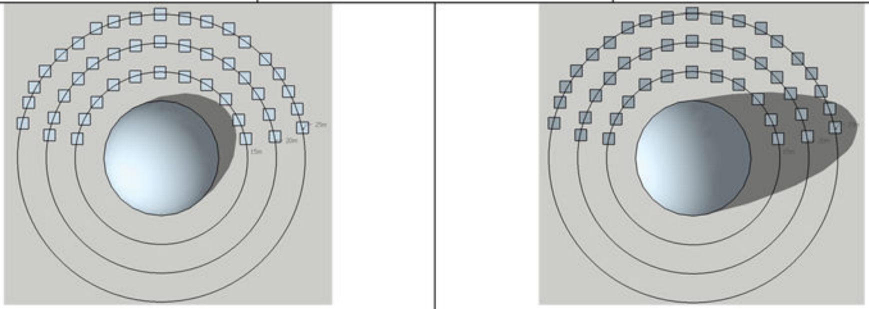

3pm September 21st

5pm September 21st

FIGURE 6. Dome shadowing for September 21st

Primary Solar Field

As mentioned earlier a primary solar field of approximately 4 MW is required to provide the heat to desalinate sufficient seawater inside the 20m diameter solar dome, the dome forming the first stage of a three-effect MED unit. For ease of installation, cost and maintenance, it is recommended to use standard parabolic trough collectors with standard evacuated tube receivers carrying oil as the heat transfer fluid. An example of an established parabolic trough design would be the EuroTrough, which has an aperture area of 5.75 m and a total collector assembly length of 150 m. A schematic showing the site layout is in Fig. 7 below, along with an indication of the location of Neom within KSA, and an image of the site with the ground works now under way.

The calculations of energy required for evaporating 200 m3/day of water gives 3.75 MWth power for 8 hours per day, a total energy of 30 MWh/day. Assuming that this is the minimum quantity required per day, the month of least DNI should be considered. This month is September, receiving 5.1 kWh/m2/day. If a solar-thermal conversion efficiency of 60% is assumed, only 3 kWh/m2/day is produced, giving a total required aperture of approximately 10,000 m2. For the 6.8 kWh/m2/day available in March, this aperture area would provide a total daily energy of 41 MWh.

To verify these calculations a solar-thermal model was created to simulate the receiver tube under incident radiation during September. The model runs for each hour of the day, using the DNI data as an input and solves non-linear equations for the heat transfer occurring in the receiver tube as the fluid is heated. The model then attempts to calculate the number of collectors required to produce the correct amount of heating of the fluid and the correct amount of total thermal power, taking into account the radiative and convective losses from the receiver. The model concluded that the total number of collector assemblies required is 12 giving a total aperture area of 9,890 m^2. This value is close to the approximation of 10,000 m2 given previously, and may be further refined by using data from the specific collector to be used. The row spacing of these parabolic troughs is typically 15 m, giving a total land size required of approximately 150 m x 180 m. The site allocated to Solar Water at Neom is 200 m x 200 m, which requires some compromises in design. In the construction phase, SENER have used an SCA separation, X = 6.76m. Therefore the mirror width is 8 SCAs x 6.868 m/SCA = 54.94m (Output > $4MW_{th}$ as designed)

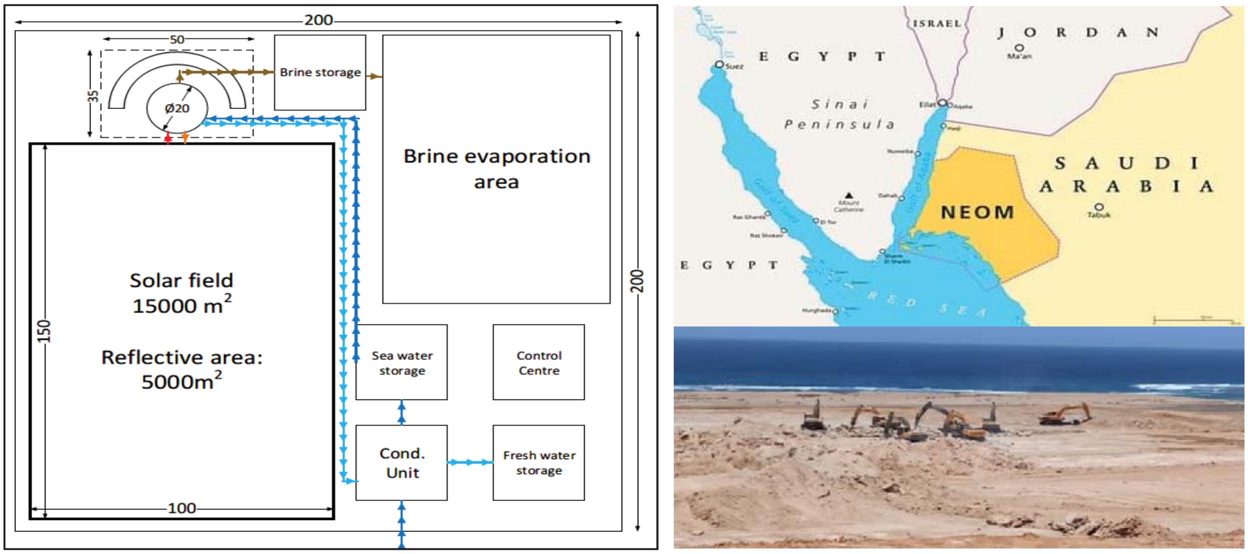

FIGURE 7. Site schematic (left); the NEOM location (top right) and the early ground works (lower right)

CONCLUSIONS

A novel CSP-enabled 3-effect MED desalination system is under construction at NEOM on the Red Sea coast of KSA. The installation is a prototype, designed and built by Solar Water plc with design consultancy provided by

Cranfield University. In this paper we described the main design philosophies, including the design of a 20m diameter geodesic dome which forms the 1st effect of the desalination process chain. The thermal energy for the process is provided from a standard parabolic trough solar collector field, supplemented by an arc of heliostats and by direct irradiance of the glass dome itself. The key components of thermal transfer, namely the primary heat exchanger and the steam exit pipe, are also briefly outlined. Construction began in the summer of 2020, and the unit is expected to be commissioned in 2021.

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REFERENCES

1. NEOM: https://www.neom.com/index.html (accessed on 14/03/21)
2. "Sun, Salt, and Saudi Megacities"; The Environment – The Magazine for the Chartered Institution of Water and Environmental Management (CIWEM) – December 2020/January 2021. https://www.ciwem.org/publications
3. https://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy (accessed on 26/09/20)
4. Solar Water plc https://www.solarwaterplc.com/ (accessed on 14/03/21)
5. C Sansom, X Tonnellier, P King, H Almond, "Concentrating Fresnel lens technology for thermal desalination", AIP Conference Proceedings 2126, 230003 (2019); https://doi.org/10.1063/1.5117767
6. Lorch, W., "Handbook of Water Purification", Second Edition ISBN 0-85312-991-6, published by Ellis Horwood Limited, England (1987).
7. Perry, R. H., Green, D. W., & Maloney, J. O. (1997). Perry's chemical engineers' handbook (ed.). Seventh, International Edition.
8. https://www.sat-control.net (accessed on 30/09/20)

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