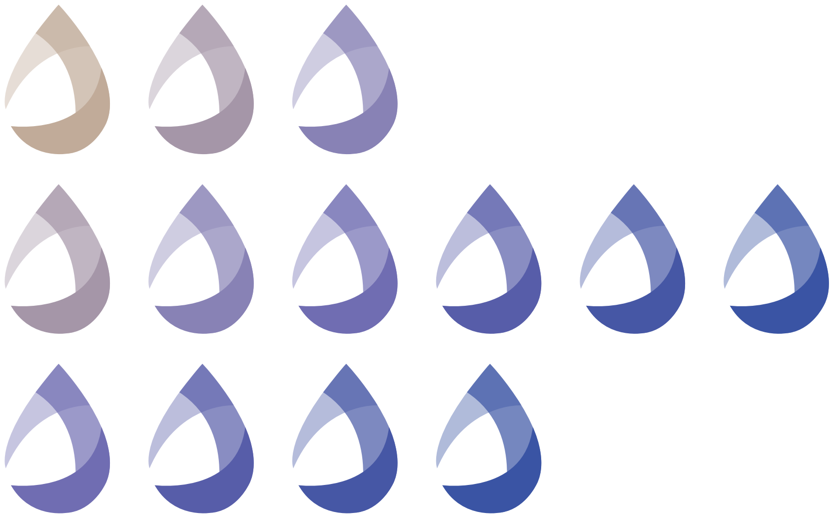

TECHNICAL PAPER

High efficiency MD modules for Solar Applications

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Version 1.1

Abstract

Normally gas powered technology and/or fossil fuels are used to be able to provide electricity and potable water (RO) in remote off-grid locations. Membrane Distillation (MD) shows a lot of potential for off-grid desalination of brackish or seawater. MD can be applied in these locations and/or cooperate with RO and other pressure driven technologies to increase water recovery and/or provide clean water where scarcity is rapidly increasing.

MD being a thermally driven technology will require a source of thermal energy. Waste heat from a variety of source such as diesel generators and Solar collectors can be used as input thermal energy for the process of MD The drawback of this solution is that the amount of thermal energy available is limited. Producing the highest possible amount of water using available solar energy is desirable in these applications. For locations with lower Solar irradiance high thermal efficiency becomes increasingly more important in order to be keep the amount of solar collectors i.e. investment costs, required ground area, thermal storage and consequently the Cost Of Water to a minimum. This high thermal efficiency is also associated with Gain Output Energy (GOR).

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The cost of water (COW) is highly dependent upon installation size (Flux) and the costs of heat (GOR) .i.e. the cost of solar collectors. For the COW there is the trade-off between installation size and Operational costs. COW of $2.72 - $2.79 were calculated under the same boundary conditions for a location in Abu Dhabi. The COW is optimal within a range of operational conditions. MD can be successfully applied within this range of operational parameters to match available thermal input. A feature ideal for solar applications.

Experimental results from a 24m^2 Aquastill module for thermal efficiency are provided matching with parameters used to determine the Cost Of Water (COW). Production rates and thermal efficiency are primarily related to water circulation flow and secondarily related to applied vacuum pressure.

The importance of thermal efficiency

In many applications there is only a given amount of thermal energy available. Being able to produce the largest amount of water with a set amount of energy is certainly desirable. 'Normal' evaporation consumes around 2260 - 2500 kJ/kg of produced water depending on the temperature (0 - 100 °C) at which evaporation occurs. If for example within the process of MD only 10% of the evaporation is be required we refer to this as 'Gain Output Ratio' (GOR) 10. The amount of water produced forw each m^2 of membrane each hour is referred as flux [ltr/m^2hr].

Providing a high GOR i.e. high thermal efficiency will reduce the amount of heat required and as such the amount of solar collectors required. Solar irradiance various for different locations and a high GOR becomes increasingly more important where solar irradiance is smaller.

This keeps the number of solar collectors, required ground surface area, thermal storages i.e.investment costs and consequently the COW to a minimum.

The process of MD is best suited to operate around the clock, providing water and minimizing downtime. Solar irradiance is however only sufficient to provide for around $^1/_3{}^{rd}$ of a day. This implies that for the remaining $^2/_3{}^{rd}$ of a day a 'buffer' of thermal energy is required to provide thermal energy. Providing a high GOR then also minimizes the size of the required buffer.

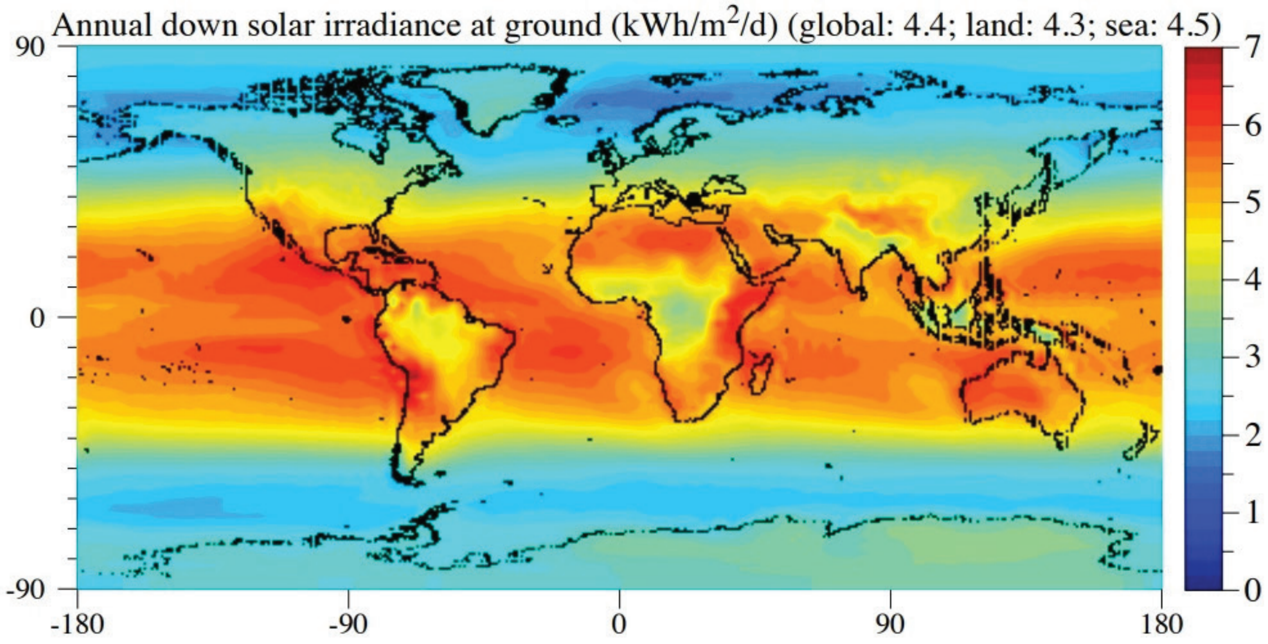

Figure 1. modelled annually averaged downward direct plus diffuse solar irradiance at ground (kWh/m^2/day) worldwide. The model used is GATOR-GCMOM (Jacobsen et al., 2007; Jacobsen, 2010a,b; Ten Hoeve et al., 2012) which simulates clouds, aerosols, gases, weather, radiation fields, and variations in surface albedo over time. Modelling with horizontal resolution 2.5° W-Ex 2.0° S-N.

The lowest Cost Of Water

The total Cost Of Water (COW) for MD is comprised from a combination of Capital expenses (CAPEX) & Operational expenses (OPEX). CAPEX Is derived from the initial investment costs for the MD installation, the hardware required to facilitate heat and coolant sources, site development and amortisation. OPEX is calculated from costs to operate the installation including electricity, chemicals or pre-treatment, disposal costs, labour, maintenance and module replacement.

As mentioned before the COW is highly dependent upon installation size (Flux) and the costs of heat (GOR) .i.e. the cost of solar collectors. High thermal efficiency modules produce more water with the same amount of heat energy. This is desirable, however for the COW there is a trade-off between low energy consumption and required installation size, it's case sensitive and it's not linear.

Displayed in figure 2 are 3 different cases with the same boundary conditions for a location in Abu Dhabi under different operational conditions. All 3 providing nearly identical COW, though having a different distribution as for the total costs of Water:

Provided the COW there is the trade-off between installation size and operational costs, MD can be successfully applied within this range of operational parameters to match available thermal input and get the most out of fluctuating thermal availability. A feature ideal for solar applications.

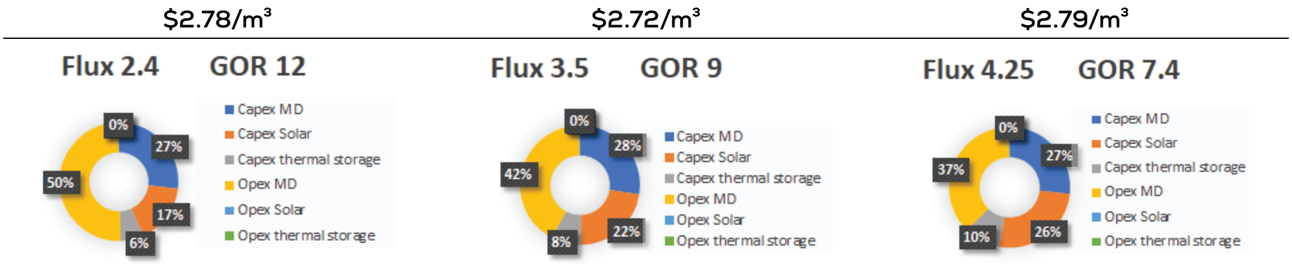

Figure 2. COW for 3 different operational conditions with the same boundary conditions:
Costs of water for different Key Performance Indicators FLUX (liters / m^2 of membrane per hour) GOR (x times more energy efficient compared to 'normal' evaporation

Aquastill MD Module Performance

Aquastill provides a range of MD modules suitable to different applications. Displayed in table 1 are the experimental results from a 24m^2 Vacuum assisted Air Gap module (V-AGMD) designed for thermal efficiency. The module was operated with brackish (4 mS) at 80-82 °C top temperature (optimal) and a variety of operational conditions (flow/ circulation debit & vacuum) to establish characteristics. More detailed graphs of the experiment can de found in the appendixes.

In the table can be seen that flux and GOR are primarily dependent on water circulation flowrate and secondly on the applied vacuum pressure. Where higher flow means higher flux and lower GOR and vice versa. the trade-off between Flux and GOR is not linear, whereas the GOR changes more as the square root of the circulation flow. Increasing the applied vacuum pressure on the module benefits both flux and GOR. Experiment graph's can be found in theappendixes . Extensive information on parameters affecting MD performance and how they relate to one another are considered in Aquastill's other technical papers.

	Flow [l/hr]	**Vacuum [mbar]**	**Flux [kg/m^2*hr^{-1}**	**GO R [–]**	**Salt rejection [%]**
1	600	-400	2	8.5	99.84%
2	600	-600	2.2	10.3	99.91%
3	600	-800	2.3	12.2	99.90%
4	1200	-700	4.25	7.4	99.86%
5	300	-800	1.2	15.6	99.60%
6	300	-600	1	13	99.73%
7	300	-400	0.93	12.2	99.83%
8	300	-200	0.9	11.8	99.90%
9	900	-800	3.5	9	99.86%
10	900	-600	3.1	8.3	99.86%
11	900	-400	2.95	7.8	99.90%
12	900	-200	2.8	7.1	99.92%

Table 1 experimental results AS24C5L

Publications including experimental results from 3rd parties using Aquastill modules in solar applications are listed in the appendixes

Appendix

Literature list:

J.A. Andrés-Mañas, A. Ruiz-Aguirre, F.G. Acién, G. Zaragoza, Performance increase of membrane distillation pilot scale modules operating in vacuum-enhanced air-gap configuration, Desalination 475 **(2020)** 114202 *doi: 10.1016/j.desal.2019.114202*

J. D. Gil, J. D. Álvarez, L. Roca, J. A. Sánchez-Molina, M. Berenguel, and F. Rodríguez, “Optimal thermal energy management of a distributed energy system comprising a solar membrane distillation plant and a greenhouse,” Energy Convers. Manag., vol. 198, no. March, p. 111791, **2019.** *https://doi.org/10.1016/j.ifacol.2019.06.048*

J. D. Gil, L. Roca, G. Zaragoza, and M. Berenguel, “A feedback control system with reference governor for a solar membrane distillation pilot facility,” Renew. Energy, vol. 120, pp. 536–549, **2018.** *https://doi.org/10.1016/j.renene.2017.12.107Get rights and content*

J. D. Gil, L. Roca, A. Ruiz-Aguirre, G. Zaragoza, and M. Berenguel, “Optimal operation of a Solar Membrane Distillation pilot plant via Nonlinear Model Predictive Control,” Comput. Chem. Eng., vol. 109, pp. 151–165, **2018.** *https://doi.org/10.1016/j.compchemeng.2017.11.012*

G. Zaragoza , J. A Andrés-Mañas and A. Ruiz-Aguirre, Commercial scale membrane distillation for solar desalination, npj Clean Water **(2018)** *1:20 ; doi:10.1038/s41545-018-0020-z*

A. Ruiz-Aguirre, J. A. Andrés-Mañas, J. M. Fernández-Sevilla, and G. Zaragoza, “Experimental characterization and optimization of multi-channel spiral wound air gap membrane distillation modules for seawater desalination,” Sep. Purif. Technol., vol. 205, no. March, pp. 212–222, **2018**. *10.1016/j.seppur.2018.05.044*

A. Ruiz-Aguirre1, J.A Andrés-Mañas2, José M. Fernández-Sevilla1, G. Zaragoza, COMPARATIVE CHARACTERIZATION OF THREE COMMERCIAL SPIRAL-WOUND MEMBRANE DISTILLATION MODULE, *doi: 10.5004/dwt.2016.11075*

A. B. Pouyfaucon and L. García-Rodríguez, “Solar thermal-powered desalination: A viable solution for a potential market,” Desalination, vol. 435, no. December 2017, pp. 60–69, **2018**. *https://doi.org/10.1016/j.desal.2017.12.025*

Alba Ruiz-Aguirre, Diego-Ce´sar Alarco´n-Padilla, Guillermo Zaragoza, Productivity analysis of two spiral-wound membrane distillation prototypes coupled with solar energy, Desalination and Water Treatment 55 **(2015)** 2777–2785 doi: 10.1080/19443994.2014.946711

John H. Lienhard,1,* Mohamed A. Antar,2 Amy Bilton,1 Julian Blanco,3 & Guillermo Zaragoza, SOLAR DESALINATION, ISSN: 1049–0787; ISBN: 1–978–56700–311–6/12/$35.00 + $00.00 **(2012)**

Experiment graph's