IS A WASTE-HEAT-INTEGRATED MULTI-EFFECT DISTILLATION TECHNOLOGY FEASIBLE AT ALL?

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EXTENDED ABSTRACT

The focus of this work pertains to the feasibility study of a novel concept based on a low-temperature waste heat integrated, solar-powered desalination system that uses Multi-Effect Distillation (MED) coupled with a Flash Vessel (FV) and Mechanical Vapour Compressor (MVC) to supply the system motive steam. A steady-state mathematical model has been developed in Python and Aspen to investigate its design, behaviour, and operation. The concept is based on a grid-dependent, scaled-up version of Desolenator's demonstrator plant project, which would see the installed capacity of produced ultra-pure distillate (TDS <2 PPM) boosted multiple times to at least forty-fold to a total of 1000 m^3 per day (averaging ca. 40 m^3/hr). Results indicate that the decrease in performance observed by operating with a higher number of effects is outweighed by the reduction of the specific power consumption (SPC) of the MVC, where an increase from four to eight effects lowers the SPC by 44.6% - crucial in reducing the PV-T array size and switching to on-site available waste heat. The integration of waste heat allows for continuous distillate production without additional storage requirements. The analysis points to the need for a flexible motive steam control scheme and its related system components. Last but not least, we will consider the capital expenditure to draw a conclusion on the feasibility of the proposed system.

Keywords: Solar-powered, Waste heat, Water, Desalination, Multi-Effect-Distillation

I. INTRODUCTION

1.1 Water-Energy Nexus

A stable water system is vital to modern society as it is central for agricultural, domestic, and industrial use [1,2]. Yet, with freshwater scarcity on the rise, these various delivery chains are being disrupted, impeding economic growth, posing a human health risk, and currently affecting over 1.2 billion people [1]. It is projected that half of the global population will live in high water-stressed regions in the next five years, resulting from a growing population, continued worldwide expansion of industrialisation, and shifting climate patterns [3].

Water is heavily intertwined with our energy systems in production and utilisation. As a result, increasing pressures on our freshwater sources and rising energy demand exacerbate our systems' vulnerability. With around 70% of the world's population situated within 200 km of an ocean coastline, desalination provides a possible pathway in addressing and meeting our future water demands, providing much-needed security [2]. As a reliable technology with decades of proven industry experience, desalination extracts salts from saline water, giving fresh water. However, it remains a very energy-intensive process. The desalination industry strongly depends on energy

from fossil fuels, accounting for 0.4% of global electrical consumption and 200 million tons of CO_2 emissions annually [4]. A means to reduce climate change is to change the energy source for water desalination to renewables. Desolenator's choice has been solar.

1.2 Solar Thermal Desalination

Over the past few decades, sustainable energy has become increasingly cost-effective and offers an attractive solution to desalination's heavy carbon footprint. Generally, there is a strong correlation between areas facing an immediate risk of high water stress levels and their corresponding high solar potential [5]. Thus, research efforts have focused mainly on coupling solar energy and desalination systems.

In this context, Desolenator has explored a novel concept based upon deploying flat plate collectors (FPCs) [8] working in conjunction with a compact, modular MED unit, both of Desolenator's proprietary designs. The company aims to exploit the low-cost, low-maintenance nature of FPCs and boost efficiency by harnessing the waste heat typically generated in PV panels. This thermal-based method of desalination offers a more climate-resilient option in dealing with changes in feed water composition, offers more flexible monitoring and operation associated with running the process when compared to its membrane-based counterparts, and can treat a broader range of water types across different industries to create its distillate [5].

Desolenator is trialling its first pilot plant in Dubai in collaboration with the Dubai Electricity and Water Authority (DEWA), see Fig. 1. The company's system uniquely combines flash steam from solar-heated water and recycled distillate vapour generated downstream to form the motive steam required to run the MED-MVC unit, as reflected in Fig. 2. The current pilot system produces up to 25 m^3 of ultrapure water distillate per day. As proof of concept, this system paves the way for targets to scale the plant 40-fold to output a minimum of 1000 m^3/day. The company aims to showcase that a decarbonised, sustainable solution can help meet growing global water demands.



Fig. 1. Photo of the Desolenator Pilot installation at DEWA

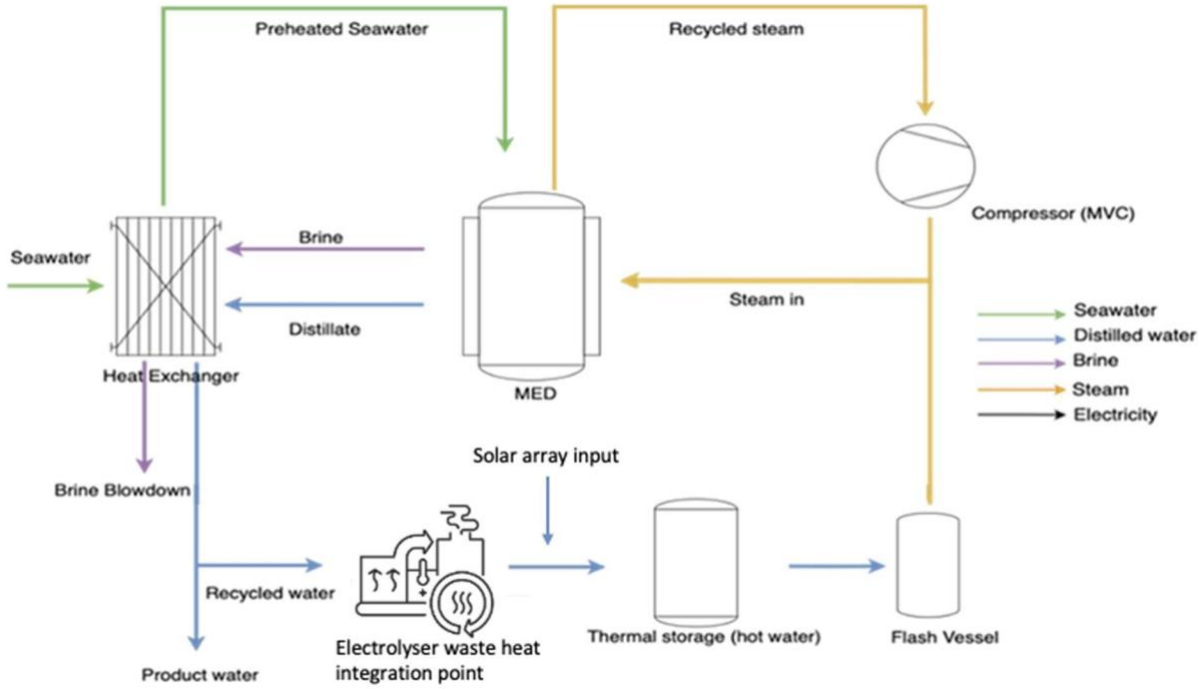

Fig. 2. Simplified process flow diagram of the desalination system integrated with waste heat illustrating main components.

1.3 Low-Grade Waste Heat

Though recent efforts and progressive research have emphasised the potential of solar coupled systems, energy storage remains necessary for the majority of these projects. This need is to ensure consistent plant power supply and to address the intermittent nature of renewable energy sources, generally constituting a substantial amount of the related project capital expenditure.

To overcome the irregular nature of sustainable energy sources and bring improved stability in operation to Desolenator's concept, the company looks to incorporate low-grade waste heat from industrial sources to partially or even fully drive its thermal process as well as supplement any electrical energy demands at night through grid electricity that its solar array can offset during the day. Globally, 50% of all energy consumed is wasted and rejected as waste heat. This waste heat exists in a spectrum of different types, forms, and qualities, but low-grade heat is most applicable for MED as it finds direct use through integration. [6] Therefore, by adopting a waste heat integration strategy, Desolenator can develop a more circular system where this energy that would have otherwise been rejected to the environment can be utilised in its MED system, thereby optimising the process efficiency, further reducing project capital expenditure, and improving distillate production and its availability over time.

1.4 Objective of Study

The objective is to introduce a novel and innovative approach to enhance the sustainability and energy efficiency of the solar thermal desalination process by integrating low-grade waste heat, for example, from co-generation plants, industrial parks or even from more recent decentralised systems such as electrolysers for green hydrogen production (where optimisation for intermittency would be matched).

Due to the unique coupling of this configuration, it is necessary to develop a model to accurately reflect critical parameters to gain a deeper understanding of plant performance under varying circumstances, to analyse required setpoints for target outputs, and to identify potential areas of improvement or optimisation.

In our research, we aim:

- to develop a comprehensive model for the integration of waste heat available on-site with the solar thermal desalination system and
- to evaluate the impact of waste heat integration on the overall system performance and energy efficiency while identifying optimal operating conditions.

This work aims to study the unique combination of FV and MVC steam inputs, balanced against the integration of waste heat and their potential effect on plant-wide efficiency improvement, total water production and stability of water provisioning. We aim to gain insights related to system feasibility and quantify the direct benefits of coupling waste heat.

II. METHODOLOGY

2.1 Model Description

A steady-state mathematical model has been developed. This consists of individual components that mirror the plant design, whereby each process is represented as a numerical block built under a set of assumptions and fluid property correlations that have been adopted or modified from previous works done on MED modelling [7]. Input and output variables of each block are linked and instantiated with initial guesses, thus creating a network of singular unit operations that can be easily modified and correspond to plant configurations and conditions at a subsystem level.
The system is set up and formulated as a non-linear optimisation problem that is iteratively solved for a given set of design constraints. These are defined as variables whose values are either fixed to replicate plant components, feed water, and location-related characteristics or set as a tolerance range to represent feasible operating condition limits and desired design outputs (capacities, temperature, pressure, composition).
This modular approach has facilitated studying different configurations and performing detailed sensitivity analyses or parametric studies, aiding the decision-making process in plant design concerning fulfilling Desolenator's scale-up goals.

2.2 Main Parameter of Interest

While a range of aspects were studied and are key to this process design, this abstract highlights the importance of maximising the highest achievable distillate production. Due to the intermittent nature of solar energy based on daily and seasonal fluctuations, it is essential to understand how plant productivity rates vary concerning the amount of available sunlight hours and how this can be best matched or supplemented with the amount and availability of existing utility heat streams as waste heat sources.

Though the plant is capable of 24-hour distillate production and a major portion of the motive steam is recaptured by the compression cycle, unlike in traditional MED-MVC systems, the bulk of distillate production must be maximised either during the daytime or periods of ample waste heat availability. Fundamentally, this extends to examining how this energy should be utilised in creating the required flash steam under various thermal efficiency schemes as defined by the plant GOR, i.e., varying the motive steam temperature (and amount) to vary the distillate production depending on the number of forecasted sunlight hours, anticipated waste heat availability, and related downtime periods tied to both.

III. DISCUSSION AND HIGHLIGHTS

3.1 Size Standardisation and TDR

We anticipate that integrating low-grade waste heat will significantly improve the Desolenator system's overall performance, potentially enhancing efficiency, water production, sustainability, and cost-effectiveness. However, the standardisation of the MED unit may limit the extent of waste heat integration, impacting its Turndown Ratio (TDR). Potential trade-offs between system standardisation and waste heat utilisation must be investigated, considering factors such as manufacturing ease and cost.

3.2 Decoupling GOR and System Flexibility

In the context of an average 40 m^3/h distillate target, preliminary data emphasise that the plant requires a flexible control scheme concerning the motive steam setpoints for mass flow and temperature, which involves components in the whole distilled water loop, as shown in Fig. 1.
Catrini et al. [8] describe the GOR as an essential indicator of fossil-fuel-based MED operational costs as it is tied closely to the motive steam supplied to the system, which is linked to fuel costs. However, this fuel cost is negligible in a solar-powered or waste-heat-driven system, and motive steam is solely based on heat availability in each respective case.

Utilising waste heat to supply motive steam can positively impact the GOR by reducing energy costs, increasing efficiency, and offering environmental benefits. However, the specific impact will largely depend on the characteristics of the waste heat source, meaning the amount and quality (type) of this heat source. It will determine the integration strategy as well as the final configuration of the system.

The early analysis highlights three distinct ideas for control schemes of low-grade waste heat integration options that are viable for this system and can be switched and bypassed as needed:

- **Upgrading heat** - whereby a waste heat source is boosted through the use of a heat pump;
- **Indirect heat exchange** - where the heat source is heat exchanged with Desolenator process water that is subsequently flashed in a flash vessel (Fig. 1); and
- **Direct flashing** - which involves the flash evaporation of this waste heat stream.

In each case, the distillate production can be turned up (overproduction), i.e., increasing the mass throughput of steam at the cost of thermal efficiency during periods of above-average solar availability and when waste heat is unavailable. In this sense, the traditional importance of the GOR becomes partially decoupled from operational costs typically associated with fossil-fuel-based MED systems. This decoupling allows for greater flexibility in distillate production.

IV. CONCLUSIONS

This research explores the potential of enhancing solar thermal desalination by integrating low-grade waste heat, offering a more energy-efficient solution for water desalination. The study's findings will inform future decisions on plant design, energy optimisation, and system flexibility, bringing us closer to achieving a sustainable water-energy nexus.

A steady-state mathematical model has been developed to simulate and characterise the performance and operation of a novel solar and waste-heat powered MED-MVC system that aims to produce 1000 m^3 of distillate daily. A further study was conducted to gain insights into the variation in daily distillate output as a function of the available sunlight hours and low-grade waste heat streams (temperature and mass flow) at varying motive steam conditions.

The preliminary study revealed that while maximising thermal efficiency during subpar weather conditions is crucial in meeting output targets, the distillate production rate can be turned up at the cost of the GOR during expected periods of above-average solar availability. Similarly, an increase in distillate production can be anticipated by integrating the waste heat. An idea for a flexible integration scheme depending on the waste heat stream's type, amount and quality has been initially suggested. It remains an open topic of ongoing research within Desolenator.

The early analysis emphasises the need for this flexible motive steam control scheme and related system components to improve plantwide efficiency, total water production, and stability of water provisioning. Also, the techno-economical results look promising.

V. REFERENCES

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