CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188205

Modelling and Simulation of Humidification-Dehumidification Process for Seawater Desalination Dual Powered by Biomass and Solar Energy

Damson Kaunga, Raj Patel, Iqbal Mujtaba*

Department of Chemical Engineering, University of Bradford, United Kingdom
I.M.Mujtaba@bradford.ac.uk

The use of solar thermal energy for water desalination processes is increasing rapidly, particularly in areas where these resources are plentiful. However, solar energy plants are highly affected by the intermittency of day –night cycles and by low irradiation seasons. Although biomass fuel can be used as source of energy for thermal desalination processes, these resources are becoming increasingly scarce, expensive and seasonally available. Integration of solar-biomass technologies for water desalination process may provide the solution to these challenges. This work investigates design options of the Humidification-Dehumidification desalination system integration with the solar-biomass energies. The investigation is based on simulation of the process models in gPROMS platform. Results show that the solar-biomass integrated plant with a thermal storage system can save up to 57 % of the daily energy cost compared to conventional biomass plant. The integrated plant also cuts the CO_2 emission by 59 %. Moreover, it has higher daily production capacity than conventional solar plants.

1. Introduction

Desalination, by convention, is defined as the process of removing dissolved solids and other minerals from water. The process is becoming necessary as per capital increase in demand for fresh water caused by population growth, urbanization and industrialization outpaces availability of high-quality water. Added to that is the global water stress caused by the effects of climate change. It is estimated that up to 2.8 billion people will face water stress or scarcity by 2030 globally and that number could reach 4 billion people by 2050 if alternative sources of water are not found (Abdelkareem et al. 2018).

There are several technologies developed by researchers to address this challenge. This includes the Humidification-Dehumidification (HDH) process. HDH is a thermal desalination cycle that operates by heating saline water and evaporating the heated water, using a humidifier, and then condensing the water vapor to produce fresh water. Various researchers have studied performance of the HDH desalination systems that uses solar energy for heating water (Mohamed et al. 2020). Being powered exclusively by solar energy, these systems can only be operated during the day when solar energy is available. This affects significantly their ability to produce fresh water continuously in a 24 h cycle.

The integration of renewable energy sources for driving the HDH water desalination systems has numerous environmental, economic and strategic advantages. The increasing water demand and climate change are factors which necessitates the development of novel water desalination technologies capable of utilizing efficiently the integrated renewable energy sources at an acceptable cost. These have advantages of ensuring the continuous supply of fresh water, at an affordable price, to consumers of all income levels. There are several studies in literature proposing the integration of energies for driving the water desalination systems. Okati et al. (2019) proposed a water production system driven by solar and geothermal energy sources capable of providing cheap drinking water at a price of 0.027 $/kg. Peng et al. (2018) also demonstrated that a solar-wind based water desalination system has high system reliability and fresh water throughput.

The use of an integrated solar thermal energy and biomass for driving the HDH water desalination systems has great potential, particularly in areas around the globe where these resources are plentiful, like most of the African and Mediterranean countries. The desalination systems driven by solar energy alone suffer from the

Paper Received: 5 June 2021; Revised: 16 September 2021; Accepted: 10 October 2021
Please cite this article as: Kaunga D., Patel R., Mujtaba I., 2021, Modelling and Simulation of Humidification-Dehumidification Process for Seawater Desalination Dual Powered by Biomass and Solar Energy, Chemical Engineering Transactions, 88, 1231-1236 DOI:10.3303/CET2188205

intermittency of day-night cycles and from reduced irradiation periods during the winter months and on overcast days. On the other hand, the biomass driven systems have to overcome the logistic problems associated with the non-continuous supply of the required amount of this seasonal fuel (Knapek et al. 2020). A hybrid system of solar thermal energy and biomass fuel is an ideal solution to overcome these limitations. It maximises the energy potential of these resources, increases process efficiency, provides greater security of supply and reduces overall production costs.

Despite these advantages, little attempts have been made to analyse performance and operating cost for the HDH desalination processes, integrated to use both solar and biomass thermal energy. Therefore, this research focuses on investigating several design options of the HDH desalination system integrated to use solar and biomass thermal energy. To achieve this goal, detailed mathematical models for the two individual processes will be developed and independently validated against literature and experimental data. Then, the integrated model will be used to investigate the performance and energy costs for several configurations and modes of operation of the integrated system. The performance indicators will include fresh water productivity, energy consumption rate, CO_2 emission rate and energy cost.

The novelty of this research is the integration of the solar thermal energy and biomass fuel to provide heating effect required for the multistage HDH water desalination system. As far as the authors are aware, there is no comprehensive work dedicated to evaluate design options and the associated influence on performance and economic factors for this type of process.

2. Process description

2.1 Common equipment and configuration

The system consists of several primary components including water storage tanks, solar collector, biomass boiler, humidifier, dehumidifier and water cooler. As shown in Figure 1, saline water circulates in a closed loop and air as an open loop. Saline water from the storage tank is heated by solar energy, if available, or by biomass boiler in absence of solar energy. Hot water from either of the heating units is sprayed on top of the first stage humidifier (H1). Rejects from this humidifier is sprayed into second stage humidifier (H2) for further recovery of fresh water and afterwards recycled back into storage tank (T1). Dry air heated at the air preheater is introduced at the bottom of stage 1 humidifier. This air is humidified by contact with hot saline water in the humidifiers.

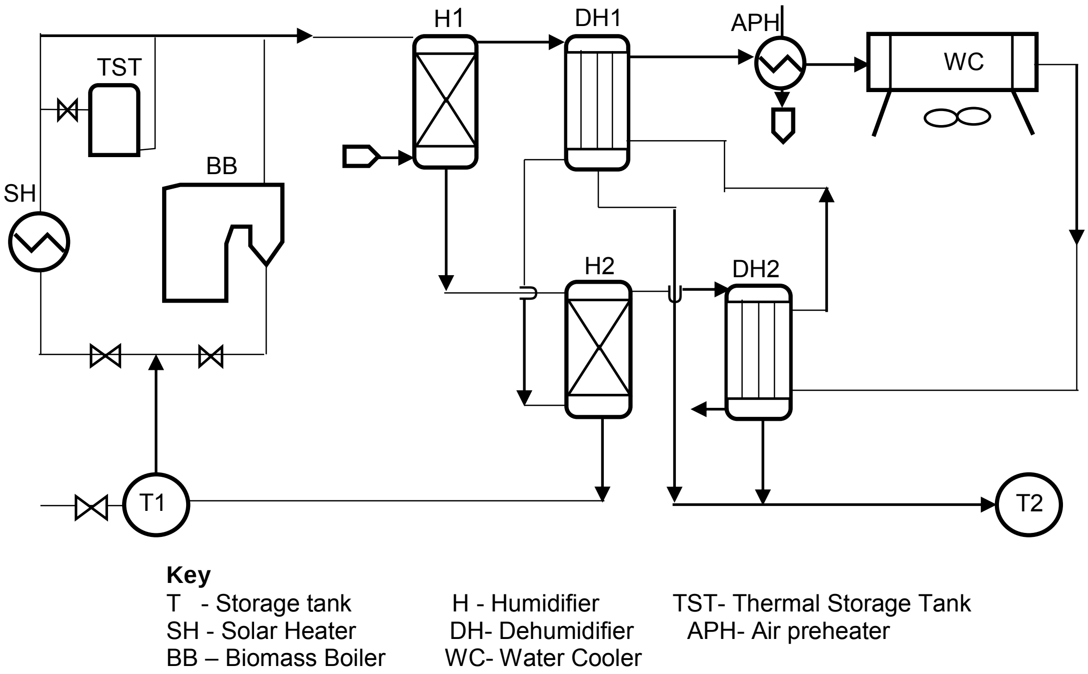

Figure 1: Process flow diagram of the hybrid HDH desalination plant

The saturated air exiting the first humidifier is cooled by passing through first stage dehumidifier to condense the water vapour. The air exiting first stage dehumidifier is introduced into 2nd stage humidifier to recover more water vapour through humidification and thereafter cooled again in 2nd stage dehumidifier for condensation of more fresh water. The water cooler (WC) is for maintaining low temperature of the cooling water in order to achieve high rates of condensation in both 1st and 2nd stage dehumidifiers. Finally, the condensate from both dehumidifiers is collected as pure water in storage tank (T2).

2.2 Modelling simulation and Validation

A solar heated multi-stage (2 stages) HDH desalination system with closed water- open air cycles is selected as base case. For comparison purpose three more cases, differentiated by changing the mode of heating were considered. These are systems heated by pure biomass, systems heated by both biomass and solar energy and finally a hybrid system incorporated with a thermal storage tank. Formulation of the main equations is based on heat and mass balance in the humidifier and dehumidifier towers as presented by Soufari et al. (2009). Air preheater is a plate-fin tubes heat exchanger modelled using equations proposed by Sievers and Lienhard (2014). The heat is transferred from the boiler/solar collectors to saline water via a circulating Heat Transfer Fluid (HTF), as shown on Figure 2b and 2c. A 1 shell pass, 2 tube passes heat exchanger used for this purpose is modelled using equations formulated by Kern (1983). The energy gained by HTF in solar collectors was calculated as

$$\dot{Q} = \dot{m}_{HTF} C_{p,HTF} \left(T_{col,in} - T_{col,out} \right) \tag{1}$$

The energy radiated on the surface of the collector is given as:

$$\dot{Q}_{sol} = \dot{Q} / \eta_{col} \tag{2}$$

The required surface area for collectors is given as

$$A_{col} = \dot{Q}_{sol} / I_T \tag{3}$$

The temperature profile of hot gases leaving the biomass fuel bed can be approximated by the gas-phase energy conservation equation as follows (Porteiro et al. 2009):

$$\frac{\partial(\emptyset \rho_g H_g)}{\partial t} + \frac{\partial(\emptyset \rho_g u_g H_g)}{\partial x} = \frac{\partial}{\partial x}\left(\lambda_g \frac{\partial T_g}{\partial x} \right) + S_a h'_s \left(T_s - T_g \right) + Q_h \tag{4}$$

The energy gained by HTF in biomass boiler is calculated as

$$Q_b = U_{ov} A F_t \frac{\left(T_{g,in} - T_{HTF,out} \right) - \left(T_{g,out} - T_{HTF,in} \right)}{ln\left(\frac{T_{g,in} - T_{HTF,out}}{T_{g,out} - T_{HTF,in}} \right)} \tag{5}$$

Biomass consumption rate in boiler is calculated as

$$\dot{m}_f = \dot{Q}_b / (\eta_b * LHV_f) \tag{6}$$

In order to simulate the model, the code is written and solved using gPROMS (Siemens, 2021) model builder software (general Process Modelling System), utilising the hierarchical sub-model decomposition procedure offered by the gPROMS language for minimising error possibilities on handling multiple primitive models. Values of the parameters used for simulation are shown in Table 1. The accuracy of any developed model should be tested before implementation to any intended purpose. The models developed in this section are validated with the results obtained from the literature. Specifically, the model validation has been carried out in terms of the fresh water productivity by comparing the prediction of developed models against the prediction of other consolidated models from literature, namely Kang et al. (2014).

Table 1: Input parameters for the simulation of the system under steady state operating condition

Parameter	Definition	Value	Unit	Parameter	Definition	Value	Unit
U_{ov}	Heat transfer coefficient	700	W/m^2 °C	$\emptyset$	Bed void fraction	0.65	-
LHV_f	Lower heating value	19.9	MJ/kg	ω_o	Humidity ratio	0.02	kg$_w$/kg$_a$
F_t	Correction factor	0.9	-	S_a	fuel surface area	600	mm^2
η_b	Boiler efficiency	0.88	-	h'_s	Heat transfer coeff	450	W/m^2 °C
I_T	Solar irradiation	450	W/m^2	T_s	solid temperature	150	°C
η_{col}	Solar collector efficiency	0.8	-	Q_h	heat gain of gas	varies	W/m^3
T_g	Flue gas temperature	varies	°C	λ_g	dispersion coeff	varies	W/m °C
T_{HTF}	Temperature of HTF	varies	°C	A	Heat exch area	30	m^2

3. Results and Discussion

In this study detailed mathematical models for the HDH desalination process integrated to use both solar and biomass energies are developed and validated as detailed in section 2. The developed models were used to compare energy requirement and daily production capacity for three cases of the system's operations. In first case the plant is operated by using biomass only. In the second case, it is operated by using solar thermal energy only while for the third case, the plant involved an integration of biomass and solar energies. For comparison purposes the system was constrained to attain an average production rate of 0.7 t/h in all cases. The daily average solar radiation rate is considered to be 450 W/m^2 (Okati et al. 2019). Full description of the input and operating parameters for the simulation is shown in Table 1.

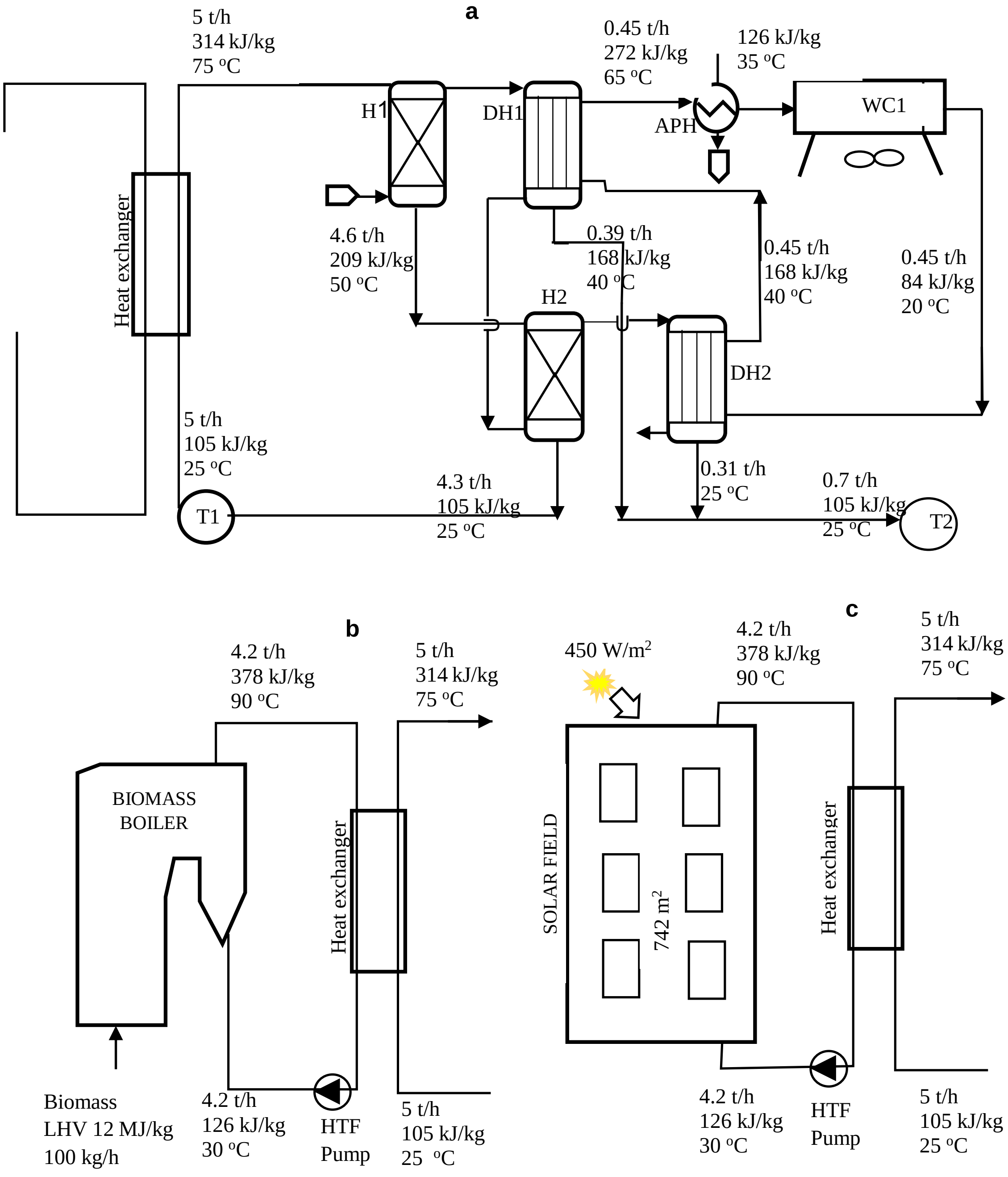

Figure 2: Detailed flow diagram for the simulated: (a) Two stages HDH desalination process (b) Biomass thermal energy production (c) Solar thermal energy production

Figure 2a shows the steady state conditions of the two stages system necessary to sustain the targeted production rate of 0.7 t/h. These are the flow-rates and streams properties for feed saline water, product (pure water) and cooling water across the units of stages 1 and 2. Figure 2b shows the fuel consumption rate of 100 kg/h for the system that draws heat exclusively from biomass. If the biomass fuel is replaced by solar thermal energy, then Figure 2c shows that a total surface area of 742 m^2 of the solar collectors is required to provide the same heating effect and maintaining the same production rate based on specified irradiation conditions of 450 W/m^2.

The key drawback of the free solar energy relates to the intermittence of its heat generation due to the day/night cycles and periods of reduced irradiation. On the other hand, the biomass combustion technology is comparatively less expensive to build but have a limited energy efficiency and high operating costs. Biomass resources are increasingly scarce, have a high cost and are available in some seasons only (Knapek et al. 2020). Therefore, to ensure longer operating hours (24 h/d) for maximum production while maintaining operating costs within reasonable and acceptable limits, a biomass boiler and solar collectors may be interconnected in parallel to form the hybrid system. From economic and environmental reasons, it is recommended to operate this hybrid plant using the solar energy whenever it is available. Biomass fuel should be used during periods of the solar absence such as nights and winter days.

3.1 Economic Assessment

The economic assessment is based on a daily production to compare the operating costs amongst the three modes of operation. The average cost of biomass used for assessment is 150 $/t (Knapek et al. 2020). For carbon dioxide, the average emission factor of 1,700 gCO_2/kg of burned dry biomass is used in this analysis (Neto et al. 2011). The possible duration for operating the solar plant is 9 h owing to an availability of the solar irradiation.

Results in Table 2 shows that, both hybrid and biomass plant have higher daily fresh water production than the solar only plant. However, the operating cost associated with hybrid plant is lower by 38 % than that of the biomass plant, owing primarily to the reduced cost for biomass fuel. By considering the production capacity and energy costs, it may be concluded that, the hybrid plant provides the maximum water production at significantly lower energy cost relative to biomass plant.

Table 2: Comparison of production capacity, energy cost and emission for the three plants

	100 % Solar Plant	100 % Biomass Plant	Hybrid Plant
Operating duration (h/day)	9	24	24
Water production (t/day)	6.3	16.8	16.8
Energy cost ($/day)	0	360	225
CO_2 Emission (t/day)	0	4.1	2.6

There is no energy cost associated with operating the solar plant as shown in Table 2. Therefore, costs for operating the hybrid plant can further be minimised by extending the use of solar thermal energy when operating the hybrid plant. Alsehli (2021) has recently proposed the thermal storage system consisting of a thermal and intermediate storage tanks. The function of this system is to store the hot feed water from solar collectors during the day and supply the HDH unit with hot feed water for several hours after solar irradiation had ceased. This technology was incorporated into the hybrid plant designed in this study in order to minimise the usage of biomass and consequently, the energy costs. Heavily insulated tanks were added to hold a portion of hot water from solar field during the day that is discharged to supply the HDH system during nights to a maximum of 5 h. Simulation results of the modified hybrid plant are compared to the previous modes of operations as shown in Table 3.

Table 3: Comparative performance and economic assessment of HDH desalination plants based on solar, biomass and hybrid technologies

	100 % Solar Plant	100 % Biomass Plant	Hybrid Plant	Hybrid Plant with Thermal tank
Operating duration (h/day)	9	24	24	24
Water production (t/day)	6.3	16.8	16.8	16.8
Energy cost ($/day)	0	360	225	150
CO_2 Emission (t/day)	0	4.1	2.6	1.7

Addition of the thermal storage system to the hybrid plant has reduced the energy cost by 33 % per day and an overall saving of 57 % relative to pure biomass plant is achieved. Although significant saving is achieved, this modification is expected to rise the initial investment costs for the modified hybrid plant in terms of construction material and labour. However, the long-term profits and benefits gained by operating the modified plant, surpasses the addition investment costs incurred to implement these modification (Moral and Petrakopoulou, 2019). Table 3 also shows that there is significant environmental benefit gained through the implemented modification. A reduction of CO_2 emission by 59 % is achieved, relative to conventional biomass plant alone.

4. Conclusions

An economic, environmental and technical assessment shows the advantages of integrating solar energy and biomass combustion technologies in water purification. HDH desalination plants heated exclusively by biomass combustion are less expensive to build compared to solar plants, but faces increasing scarcity of the fuel, high cost and seasonal availability. In contrast, HDH desalination plants heated exclusively by solar energy benefit from the use of a freely available source of energy, but affected by the intermittency of the day/night circles and periods of low irradiation such as winter seasons.

This paper suggests the use of a HDH water desalination plant with integrated solar-biomass energies. It also provides a preliminary technical, economic and environmental analysis of the integrated plant as an alternative to conventional desalination plants heated by solar or biomass only. The results show that, solar-biomass energy integration has net effect of reducing the energy cost by 38 % compared to a pure biomass plant. At the same time, it maximizes the effective operating hours and overall daily production capacity of the HDH desalination plant. The highest daily fresh water production achieved is 16.8 t. Finally, the modification of an integrated plant by incorporating the thermal storage system lowers further the energy cost, whereby, an overall daily saving of 57 % is achieved. Not only that, it also reduces the CO_2 gas emission by 59 % compared to the pure biomass plant.

Acknowledgements

The authors wish to thank the Commonwealth Scholarship Commission in the UK (CSC) for financial support under PhD Scholarships Plan for Low and Middle Income Countries.

References

Abdelkareem M., Assad E., Sayed E., Soudan B., 2018. Recent progress in the use of renewable energy sources to power water desalination plants, Desalination, 435, 97-113.

Alsehli M., 2021. A New Approach to Solar Desalination Using a Humidification–Dehumidification Process for Remote Areas, Processes, *9*, 1120.

Kang H., Yang Y., Chang Z., Zheng H., Duan Z., 2014. Performance of a two-stage multi-effect desalination system based on humidification–dehumidification process, Desalination, 344, 339–349.

Kern D., 1983. Process Heat Transfer. McGraw-Hill, London, UK.

Knapek J., Kralik T., Vavrova K., Weger J., 2020. Dynamic biomass potential from agricultural land, Renewable and Sustainable Energy Reviews, 134, 2020.

Mohamed A., Ahmed M., Maghrabie H., Shahdy A., 2020. Desalination process using humidification–dehumidification technique: A detailed review. International Journal of Energy Research, 45, 3698–3749.

Moral A., Petrakopoulou F., 2019. Evaluation of the Coupling of a Hybrid Power Plant with a Water Generation System. Applied Sciences, 9, 4989.

Neto T., Carvalho J., Cortez E., Azevedo R., Oliveira R., Fidalgo W., 2011. Laboratory evaluation of Amazon forest biomass burning emissions, Atmospheric Environment, 45, 7455-7461.

Okati V., Ebrahimi A., Behzadmehr A., Farzaneh-Gord M., 2019. Proposal and assessment of a novel hybrid system for water desalination using solar and geothermal energy sources, Desalination, 467, 229–244.

Peng W., Maleki A., Rosen M., Azarikhah P., 2018. Optimization of a hybrid system for solar-wind-based water desalination by reverse osmosis: Comparison of approaches, Desalination, 442, 16-31.

Porteiro J., Collazo J., Patino D., Granada E., 2009. Numerical Modeling of a Biomass Pellet Domestic Boiler, Energy & Fuels, 23, 1067–1075.

Sievers M., Lienhard J., 2015. Design of Plate-Fin Tube Dehumidifiers for Humidification–Dehumidification Desalination Systems, Heat Transfer Engineering, 36, 223-243.

Soufari S., Zamen M., Amidpour M., 2009. Performance optimization of the humidification–dehumidification desalination process using mathematical programming, Desalination, 237, 305-317.

Siemens PSE, 2021, The gPROMS platform, Siemens Process Systems Engineering, <https://www.psenterprise.com/products/gproms/platform>, accessed 24.06.2021.