Multi-Objective Optimization of Renewable Energy-Driven Desalination Systems

Viviani C. Onishi*, Rubén Ruiz-Femenia, Raquel Salcedo-Díaz, Alba Carrero-Parreño, Juan A. Reyes-Labarta, José A. Caballero

Institute of Chemical Process Engineering, University of Alicante, Ap. Correos 99, Alicante 03080, Spain

viviani.onishi@ua.es

Abstract

Environmental impacts related to increasing greenhouse gas emissions and depletion of fossil-fuel reserves and water resources are major global concerns. In this work, we introduce a new multi-objective optimization model for simultaneous synthesis of zero-emission desalination plants driven by renewable energy. The system is particularly developed for zero-liquid discharge (ZLD) desalination of high-salinity shale gas wastewater, aiming to enhance economic and environmental system performance. The mathematical model is based on a multistage superstructure, which integrates a solar assisted Rankine cycle to a multiple-effect evaporation with mechanical vapor recompression (MEE-MVR) plant. For achieving the goal of more sustainable ZLD process, we specify the discharge brine salinity near to salt saturation conditions. The model is formulated as a multi-objective multiperiod non-linear programming (NLP) problem. The model is implemented in GAMS and solved via epsilon-constraint method, through the minimization of total annualized cost and environmental impacts. The economic objective function accounts for capital cost of investment and operational expenses, while environmental criteria are quantified by the life cycle assessment (LCA)-based ReCiPe methodology. A case study is performed to demonstrate the capabilities of the developed model. The obtained set of trade-off Pareto-optimal solutions reveals that integration of renewable energy generation to ZLD desalination plants can lead to significant cost and environmental savings for shale gas industry.

Keywords: Multi-objective optimization, zero-liquid discharge (ZLD), solar energy, Rankine cycle, life cycle assessment (LCA).

1. Introduction

In shale gas industry, single/multiple-effect evaporation systems with mechanical vapor recompression (SEE/MEE-MVR) can be applied for desalting the large amounts of high-salinity wastewater from gas extraction. Although these desalination systems have proven to be cost-competitive feasible alternatives, elevated energy demand and environmental impacts have been disregarded during their design task. We emphasize that electrical power consumption and brine discharges represent the main sources of environmental impacts in these desalination processes. In consequence, sustainable and more efficient desalination plants should be implemented for shale gas wastewater treatment. The latter should include the development of environment-friendly and cost-effective zero-emission systems, as well as the integration of renewable energy generation to drive the process.

Zero-liquid discharge (ZLD) systems have emerged as promising alternatives for high-salinity applications, including the treatment of flowback water from shale gas production. Onishi et al. (2017a) proposed a mathematical model for the optimal design of zero-emission SEE/MEE-MVR processes. Their optimization results highlight the potential of ZLD plants for the effective and economic desalination of shale gas wastewater. Afterward, the authors extended their previous study to address the rigorous design of zero-emission MEE-MVR desalination systems (Onishi et al., 2017b). Hybrid processes for integrating renewable energy into desalination systems have also attracted interest from both academia and industry. Chafidz et al. (2016) developed a hybrid solar-driven membrane distillation system to produce freshwater from seawater. Also, Bataineh (2016) presented a simulation model for the seawater desalination via evaporation process powered by a solar steam generation plant.

In this work, we introduce a new multi-objective mathematical model for the optimal design of renewable energy-driven desalination plants. The zero-emission system is especially applied to the desalination of high-salinity shale gas wastewater, aimed at enhancing both economic and environmental system performance. The optimization model is based on a multistage superstructure that integrates the solar assisted Rankine cycle to the MEE-MVR desalination plant. Yet, a more environment-friendly ZLD process is ensured by a design constraint, which allows outlet brine salinity near to salt saturation conditions. The multi-objective multiperiod NLP-based model is implemented in GAMS and optimized via epsilon-constraint method, through the minimization of total annualized cost and environmental impacts. The economic criterion is evaluated by capital investment and operating expenses, while the environmental objective function accounts for all energy consumption-related impacts. The environmental criteria are quantified following the life cycle assessment (LCA) principles via ReCiPe methodology. We construct a Pareto-optimal frontier to guide decision-makers towards the application of more sustainable and economical ZLD desalination systems in shale gas industry.

2. Problem Statement

To address the problem of multi-objective optimization of renewable energy-driven ZLD systems, we consider a high-salinity wastewater stream from shale gas production with given inlet condition (including temperature, salt concentration and flowrate) and target (zero-emission) state. Additionally, equipment for the MEE-MVR desalination system (composed by multiple-effect evaporator, flashing tanks, mechanical vapor compressor, preheater, mixers and pumps), coupled to a solar assisted Rankine cycle (composed by solar parabolic trough collectors, gas fired heater, heat exchangers and turbine) are also available with their related capital investment. Weather conditions are known input design parameters for the multiperiod model. Energy services (natural gas, electricity and cooling water) are also provided with their corresponding environmental and cost data. The multi-objective model is aimed at obtaining an optimal ZLD desalination system design with integrated solar energy generation, and operational conditions that simultaneously enhance its economic and environmental performance. The solar Rankine cycle should be properly operated in multiperiod weather conditions, while minimizing brine releases. For this purpose, zero-emission operation is ensured by a design constraint that allows discharge brine salinity near to salt saturation condition (300 g kg^{-1}). The multi-objective multiperiod non-linear programming (NLP) model is optimized using the epsilon-constraint method, through the minimization of total annualized cost and environmental impacts. The economic objective function accounts for capital investment and operational expenses, while the environmental criteria are evaluated by the (LCA)-based ReCiPe methodology. The superstructure and process description are presented as follows.

3. Superstructure and Process Description

The multistage superstructure for the solar energy-driven ZLD desalination system is displayed in Figure 1. The overall process is composed by three different subsystems: MEE-MVR desalination plant coupled to Rankine cycle unit and solar energy system.

3.1. MEE-MVR Desalination System

The MEE-MVR desalination plant comprises multiple-effect horizontal-tube evaporator connected to intermediate flash tanks to enhance energy recovery. Thermal integration is further increased through a feeding-distillate preheater, while all vapor formed by flashing and evaporation is operated by a mechanical compressor. Additional details on MEE-MVR systems can be found in our previous studies (Onishi et al. 2017a; 2017b).

3.2. Rankine Cycle Unit

The Rankine cycle unit produces electric power needed to drive the mechanical vapor compressor of the MEE-MVR plant. In this system, the sub-cooled working fluid (i.e., water) is converted into superheated vapor by exchanging heat with the thermal fluid from the solar energy unit. The superheated vapor passes through a turbine, which allows electricity generation by its expansion. The Rankine cycle is closed by a condenser (using cooling water) that convert saturated vapor at low pressure from the turbine generator into condensate, which is pumped back to the heat exchanger to restart the cycle.

3.3. Solar Energy Unit

Parabolic trough collectors are employed in the solar energy unit to transfer energy to the thermal fluid (i.e., mineral oil). A gas fired heater powered by natural gas is used to respond to energy shortages resulting from daily solar intermittency. The latter equipment safeguards constant energy supplying to the MEE-MVR desalination plant, by maintaining the thermal fluid at constant temperature.

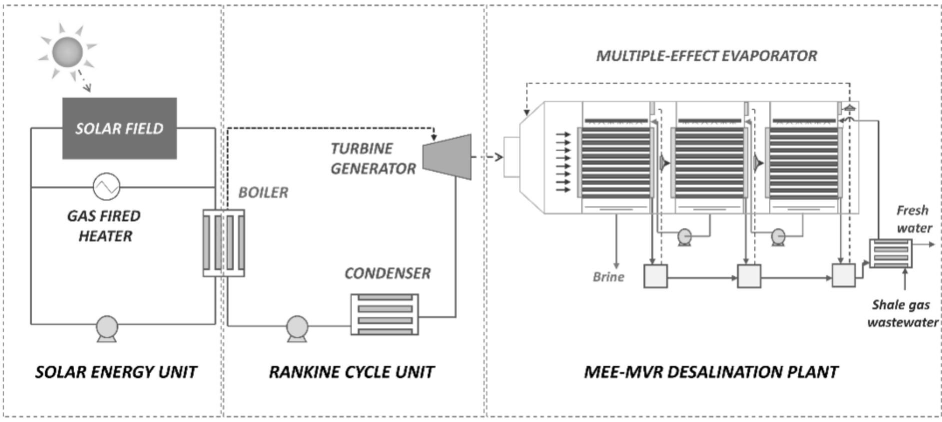

Figure 1. Multistage superstructure for the solar energy-driven ZLD desalination system.

4. Multi-Objective Mathematical Model

The multi-objective multiperiod NLP-based model includes modelling equations for the optimal design of the MEE-MVR plant, Rankine cycle unit and solar thermal system and objective functions. The mathematical formulation for the MEE-MVR desalination system is based on our previous optimization models presented in Onishi et al. (2017a; 2017b). Thus, the MEE-MVR model involves mass and energy balances, pressure and temperature feasibilities and design constraints on temperatures and ZLD specification. The ZLD constraint is used to restrict the search space to feasible solutions that meet the minimum requirement on the discharge brine salinity S^{design}. Thus, the zero-emission operation is ensured by the following inequality:

$$S_i^{brine} \geq S^{design} \qquad i = 1 \tag{1}$$

In which S_i^{brine} indicates the brine salinity in the first effect i of the evaporator. Note that the system is under backward feeding configuration. The MEE-MVR plant is connected to the solar assisted Rankine cycle unit by the following design constraint:

$$W^{RC} \geq W^{MEE-MVR} \tag{2}$$

This restriction ensures that the work produced in Rankine cycle should be greater or equal than mechanical energy required by the compressor in the MEE-MVR plant. Note that the net power produced in the Rankine cycle should be given by the difference between the power generated by the turbine and the small amount consumed by the pump:

$$W^{RC} = W_{turbine} - W_{RC\_pump} \tag{3}$$

The solar energy unit should be designed by considering different time periods t that accounts for the variation in daily solar irradiance throughout the year. In the solar system, the heat demands of the boiler Q_t^{boiler} should be satisfied by the energy provided by the solar collectors Q_t^{collec} and the gas fired heater Q_t^{gfh} in all different time periods. Thus, the global energy balance in the solar thermal unit can be expressed as follows:

$$Q_t^{boiler} = Q_t^{collec} + Q_t^{gfh} \qquad \forall t \in T = \{t / t = 1, 2, ..., T \text{ are time periods}\} \tag{4}$$

As aforementioned, the resulting multi-objective NLP model is optimized through the minimization of the total annualized cost (TAC) and environmental impacts (EI). The economic objective function is given by the Eq. (5), comprising the capital investment $CAPEX$ in equipment and operating expenses $OPEX$ associated to energy consumption in the process.

$$TAC = CAPEX + OPEX \tag{5}$$

The environmental criteria consider the overall impacts related to thermal services and electricity consumed, which are quantified through the LCA-based ReCiPe methodology. The environmental objective function is given by the following equation:

$$EI = f_{EI}\left[\sum_{t\in T} LCIA_{electricity}\cdot\left(\frac{W_t^{ss\_pump}}{np}\right)+\sum_{t\in T} LCIA_{gas}\cdot\left(\frac{Q_t^{gfh}}{np}\right)+LCIA_{cooling}\cdot Q^{condenser}\right] \qquad (6)$$

The environmental impacts are estimated by the total ReCiPe points (Ecoinvent default, LCIA, ReCiPe Endpoint (H/A), Europe/Es) by year obtained from Ecoinvent database (version 3.3). The multi-objective NLP model was implemented in GAMS (version 24.7.4) and solved using the epsilon-constraint method (Ehrgott, 2005). The local optimizer CONOPT3 was used to solve the problem with CPU time of ~10 min, considering 180 distinct time periods for 20 alternative Pareto-optimal solutions. The model was solved with a personal computer with an Intel Core i5-2520M 2.5 GHz processor and 8 GB RAM running Windows 10. Clearly, lower and upper bound on all decision variables are critical to solve the model and reduce the computational effort.

5. Case Study

We perform a case study to illustrate the capabilities of our proposed multi-objective NLP model to optimize solar-driven ZLD desalination systems. The MEE-MVR plant is designed to be capable to treat 10.42 kg s^{-1} of shale gas wastewater. The feed water salinity is equal to 70 g kg^{-1}, while the discharge brine salinity should reach the ZLD condition (300 g kg^{-1}). Additional data for the MEE-MVR system design can be found in the references (Onishi et al. 2017a; 2017b). In the solar thermal unit, we consider parabolic trough collectors due to their higher efficiencies at high temperatures. The performance data for solar collectors, as well as process parameters, Spain's weather data and physical properties correlations are extracted from Salcedo et al. (2012).

The Pareto-optimal frontier obtained by applying the epsilon-constraint method is displayed in Figure 2. In this figure, Design A indicates the extreme solution that corresponds to the minimum environmental impact solution. In this case, the optimal extreme solution requires a total solar collector area of $5.2\text{x}10^5$ m^2. In contrast, Design B represents the minimum cost extreme solution (2154 kUS\$ y^{-1}), which no collectors are used in the system. Results from these extreme solutions reveal that it is possible to obtain ~84 % of environmental savings by adding solar collectors. Although the total cost for Design A can be prohibitive (42074 kUS\$ y^{-1}), trade-off optimal solutions between designs B and C show significant decrease in environmental impacts (~79 %) with lower cost increment. Design C presents a total annualized cost equal to 4407 kUS$ y^{-1} (~90 % lower than Design A), requiring 21.9×10^3 m^2 of solar collectors' area.

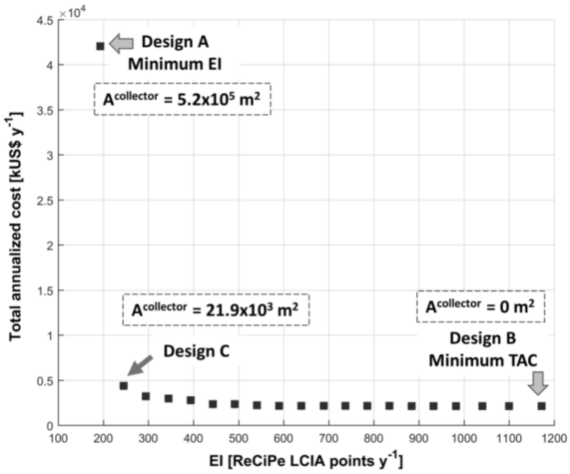

Figure 2. Set of alternative Pareto-optimal solutions obtained for the case study.

6. Conclusions

A new multi-objective optimization model is introduced for the simultaneous design of ZLD desalination plants driven by renewable energy. The zero-emission system is specially applied to the shale gas wastewater desalination. A multistage superstructure is proposed for the process, integrating a solar assisted Rankine cycle to the MEE-MVR plant. ZLD operation is ensured by a design constraint that specifies the discharge brine salinity close to salt saturation conditions. The solar energy unit is designed to operate along different time's periods according the daily solar irradiance throughout the year. The resulting multi-objective multiperiod NLP model (implemented in GAMS) is solved via epsilon-constraint method, through the minimization of total annualized cost and environmental impacts. The economic objective function includes the capital investment and operating expenses, whist environmental criteria are evaluated by the LCA-based ReCiPe methodology. A case study is carried out to illustrate the applicability of the proposed approach as the optimal ZLD desalination process design.

A set of alternative Pareto-optimal solutions is obtained, showing that the renewable energy integration into ZLD desalination systems can lead to significant cost and environmental savings is shale gas industry. The optimal Pareto frontier reveals that important environmental impacts reduction (~84 %) can be obtained by installing solar collectors in the system. Although some trade-off solutions can be economically prohibitive (e.g., Design A), solutions between designs B and C can be selected for the application of more economical and sustainable solar-driven ZLD desalination systems.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 640979.

References

Bataineh K.M., 2016. Multi-effect desalination plant combined with thermal compressor driven by steam generated by solar energy. Desalination 385, 39–52.

Chafidz A., Kerme E.D., Wazeer I., Khalid Y., Ajbar A., Al-Zahrani S.M., 2016. Design and fabrication of a portable and hybrid solar-powered membrane distillation system. Journal of Cleaner Production 133, 631–647.

Ecoinvent database (V3.3), Swiss Centre for Life Cycle Inventories, Zurich, Switzerland, 2016.

Ehrgott M., 2005. Multicriteria optimization. Springer Verlag, New York.

Onishi V.C., Carrero-Parreño A., Reyes-Labarta J.A., Ruiz-Femenia R., Salcedo-Díaz R., Fraga E.S., Caballero J.A., 2017a. Shale gas flowback water desalination: single vs multiple-effect evaporation with vapor recompression cycle and thermal integration. Desalination 404, 230–248.

Onishi V.C., Carrero-Parreño A., Reyes-Labarta J.A., Fraga E.S., Caballero J.A., 2017b. Desalination of shale gas produced water: A rigorous design approach for zero-liquid discharge evaporation systems. Journal of Cleaner Production 140, 1399–1414.

Salcedo R., Antipova E., Boer D., Jiménez L., Guillén-Gosálbez G., 2012. Multi-objective optimization of solar Rankine cycles coupled with reverse osmosis desalination considering economic and life cycle environmental concerns. Desalination 286, 358–371.