Multi-Objective Optimization of Renewable Energy-Driven Desalination Systems

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Introduction

- In shale gas industry, multiple-effect evaporation systems with mechanical vapor compression (MEE-MVC) can be applied for desalting the high-salinity wastewater generated from natural gas extraction
- Although MEE-MVC systems have proven to be cost-competitive alternatives, elevated energy demand and related environmental impacts have been disregarded during their design task
- Electrical power consumption and brine discharges are the main sources of environmental impacts in conventional MEE-MVC desalination processes
- Hence, more sustainable and efficient zero-liquid discharge (ZLD) desalination plants should be developed for the treatment of shale gas wastewater
- In this work, a new multi-objective mathematical optimization model is introduced for the design of solar energy-driven zero-emission MEE-MVC plants

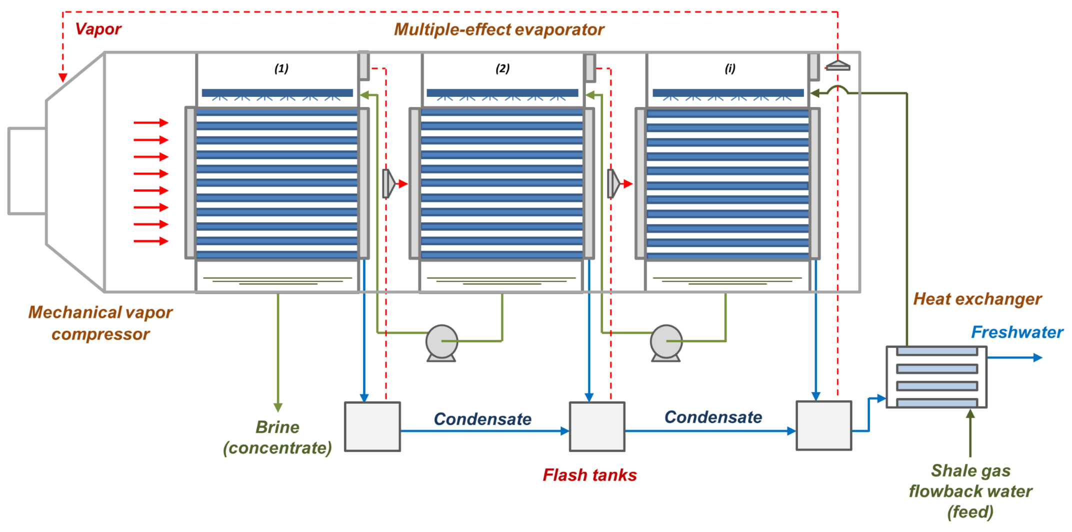

Figure 1. General superstructure proposed for the MEE-MVC desalination plant of shale gas wastewater (Adapted from [1,2])

Problem Statement

- The multi-objective model is aimed at obtaining an optimal zero-emission MEE-MVC system design, with integrated solar energy generation and operational conditions that simultaneously enhance its economic and environmental performance
- The ZLD desalination system is especially applied to the desalination of high-salinity shale gas wastewater
- The solar Rankine cycle should be properly operated by multiperiod weather conditions, while minimizing energy consumption and brine releases
- For this purpose, zero-emission operation is ensured by a design constraint that allows discharge brine salinity close to salt saturation conditions (300 g kg^{-1})

Multistage Superstructure

- The overall process is composed by three different subsystems: a MEE-MVR desalination plant coupled to a Rankine cycle unit and a solar energy system. The multistage superstructure for the solar energy-driven ZLD desalination system is displayed in Figure 2
- The MEE-MVR desalination plant comprises a multiple-effect horizontal-tube evaporator connected to flashing tanks and preheater to enhance energy recovery. In addition, vapor formed by flashing and evaporation is operated via a mechanical compressor
- The Rankine cycle unit produces electric power needed to drive the mechanical vapor compressor in the MEE-MVR plant
- 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

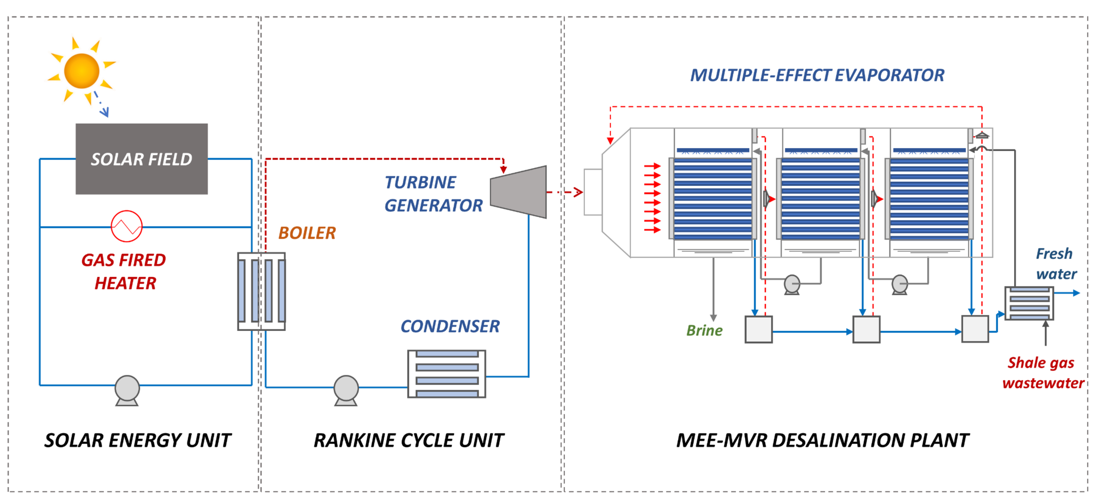

Figure 2. Multistage superstructure proposed for the solar energy-driven zero-emission MEE-MVC desalination system

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
- Thus, the 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. The ZLD operation is ensured by the following inequality:

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

- The MEE-MVR plant is linked to the solar-assisted Rankine cycle unit by the following design constraint:

$$W^{RC} \geq W^{MEE-MVR} \qquad (2)$$

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

$$W^{RC} = W_{turbine} - W_{RC\_pump} \qquad (3)$$

- The resulting multi-objective multiperiod NLP-based model was optimized in GAMS via epsilon-constraint method, through the minimization of process total annualized cost (TAC) and environmental impacts (EI)
- The economic objective function accounts for capital investment and operational expenses, while the environmental criteria are evaluated by the (LCA)-based ReCiPe methodology (Ecoinvent database)
- The solver CONOPT4 was used to optimize the problem with CPU time of ~9 min, considering 180 distinct time periods for 20 Pareto-optimal solutions

Case Study

- 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
- In Figure 3, Design A indicates the extreme solution that corresponds to the minimum EI solution. This solution needs a total collectors' area of 5.2x10^5 m^2
- In contrast, Design B represents the minimum TAC extreme solution, in which no collectors are required
- Trade-off optimal solutions between designs B and C show significant decrease in EI (~79%) with lower cost increment
- Design C presents a TAC ~90% lower than Design A, requiring 21.9x10^3 m^2 of solar collectors' area

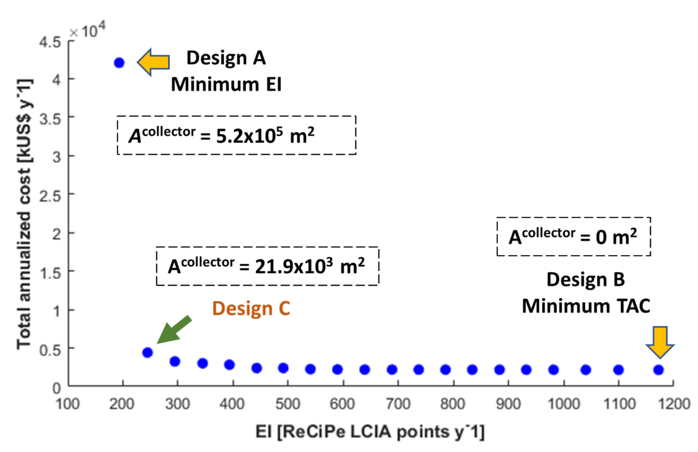

Figure 3. Set of alternative Pareto-optimal solutions obtained for the case study

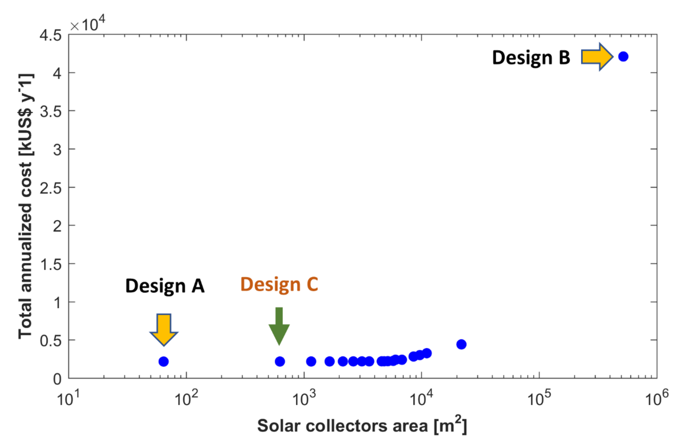

Figure 4. Dependence of the total annualized cost of the ZLD system on the total solar collectors' area

Conclusions

- A set of alternative Pareto-optimal solutions is obtained, showing that the solar energy integration into ZLD desalination systems can lead to significant cost and environmental savings for 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 optimal 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
- These results can be used to guide decision-makers from shale gas industry towards a cleaner future

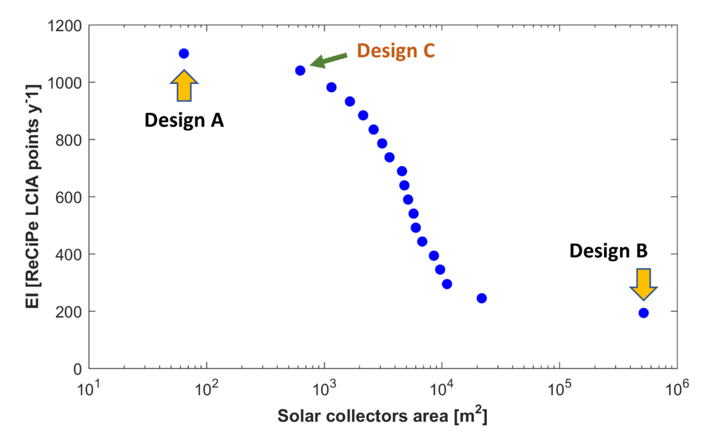

Figure 5. Dependence of the total environmental impacts of the ZLD system on the total solar collectors' area

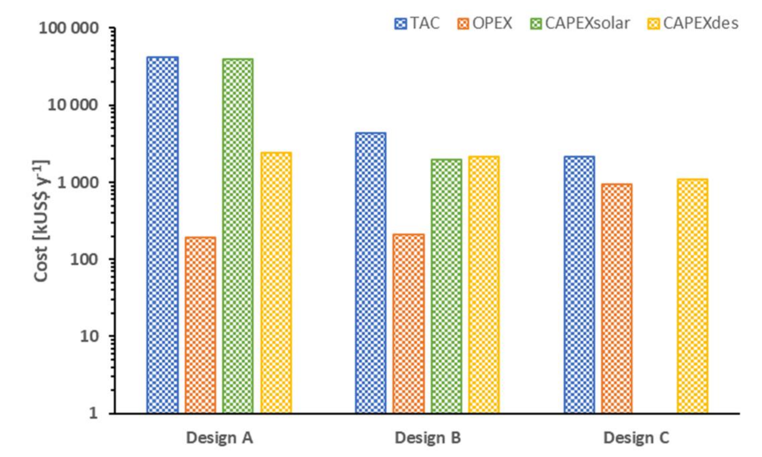

Figure 6. Cost breakdown for the Pareto-optimal designs

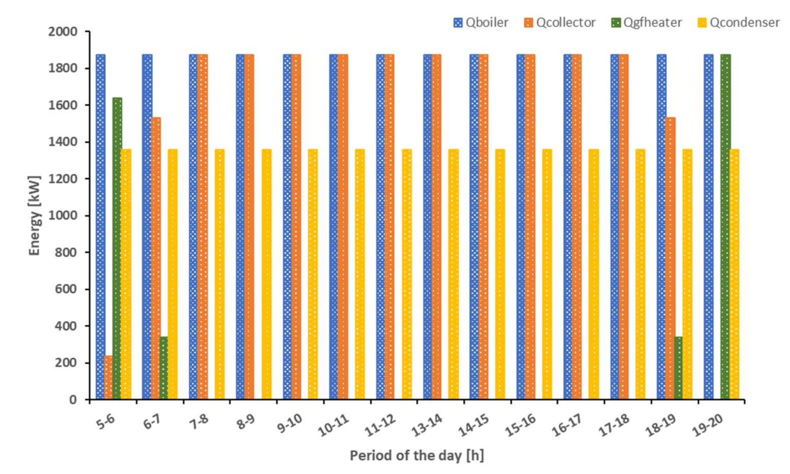

Figure 7. Energy flows in June for the Design C

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