Ultra-Efficient Solar-Thermal Batch Reverse Osmosis with Novel Thermal RO Engine

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Table of Contents

1. Executive Summary **1**

2. Background and introduction **2**

3. Technical Approach and Project Activities **5**

Mitigation of Challenges and Risks 9

4. Research Work Plan and Schedule **10**

Task 1 Thermodynamic system modeling of t-BRO (M1-M16) *10*

Task 2 Developing batch reverse osmosis system (BRO) (M1-M8) *11*

Task 3 Integrating Stirling engine with BRO (M4-M18) *11*

Task 4 Investigating fouling with a bench-scale BRO system (M1-M24) *12*

6. Research work plan and schedule **14**

7. Quality assurance/quality control (QA/QC) **15**

8. Facilities and equipment information **16**

9. Environmental Impact **16**

10. Responses to evaluation criteria **17**

11. References **20**

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1. Executive Summary

Solar desalination has great potential to sustainably increase our water resources, but current hybrid technologies are too inefficient to be practical or affordable [1]. Existing solar-thermal desalination systems can only use low temperature heat (<120 °C), causing them to waste most of the available work that solar concentration can provide and requiring unreasonably large solar collection areas [1]. In order to fill the gap in existing RO and energy requirements, we propose to develop a novel solar groundwater desalination system that achieves high efficiency by directly converting high-temperature (>500 °C) solar heat to pump power, which drives an efficient batch reverse osmosis (BRO) unit. In such a system, a solar concentrating dish efficiently provides heat to a Stirling engine, which will be directly coupled to the shaft of the BRO unit's high-pressure pump.

BRO is predicted to be the most efficient method for moderate-salinity groundwater [2,3] desalination, enabling a scaled-up solar-powered system to achieve a record-breaking efficiency of 10% (4 kWh_{solar}/m^3). Previously, the applicants won Reclamation's 2017 "More Water, Less Concentrate Challenge" by demonstrating that BRO has the potential to reach high efficiency, fouling resistant, lower costs, and reach higher concentrations than traditional reverse osmosis [3].

By making the best use of high-temperature solar radiation, maximizing desalination efficiency, and eliminating inefficient energy conversions, a full-scale thermal BRO (t-BRO) system has the potential to produce 10× the water of a solar Multi-Effect Distillation (MED) system from the same amount of sunlight. Consequently, this proposed laboratory-scale prototype will pare the concept down to its essentials by replacing the concentrating dish with a small furnace and coupling a high-efficiency Stirling engine through a transmission to a pump that will drive a batch reverse osmosis cycle. By eliminating conversion to and from electricity and using batch RO, we seek to demonstrate that for low energy consumption and high fouling resistance, the cost of water desalination is lower than existing products.

In terms of impact, the current project we will refine and validate thermodynamic models of BRO and t-BRO to predict the performance of a full-scale system and determine whether the technology is a candidate for pilot-scale testing with sunlight and real groundwater. A successful outcome of the project will demonstrate a thermally-driven batch RO process at lab scale. Furthermore, it will produce data paired with modeling to show the potential achievable energy efficiency versus salinity and recovery. Ideally, it will set the stage for future work with a pilot that can demonstrate solar thermal RO as the most efficient solar thermal desalination technology, and that batch RO can desalinate groundwater to higher recovery than traditional RO.

This addresses several priorities of the WIIN Act and the FOA's objectives by reducing the energy consumption and environmental impact of desalination, improving reverse osmosis technology, powering desalination with renewable energy, and testing a new approach to concentrate management. The demonstration of this new concept will help open up a field of research for much more efficient renewable desalination systems that would produce low cost of water. This work will be completed in 24 months with an estimated range of 3/1/2020-2/28/2022. It will not be done in a federally or state-funded facility.

2. Background and introduction

Although the need for freshwater is perpetual, using fossil fuels to power most of the world's desalination plants releases CO_2, threatening our climate and potentially exacerbating water scarcity. More importantly, is that existing systems based on nuclear, coal or other fossil fuel derived power plants use water in the cooling cycle—thus the current technology based on renewable energy minimize the use of water to then produce water desalination. Using renewable sources of energy such as solar, wind, and geothermal to produce freshwater as energy-efficiently and cost-effectively as possible can help minimize the negative environmental impacts while also reducing the use for water for energy. The energy requirements of reverse osmosis (RO)—today's most energy-efficient process for moderate-salinity groundwater desalination—have improved considerably in recent decades [1,3] due to innovations in membranes, pumps, and energy recovery. However, RO plant energy efficiency is still far from 100%: large-scale seawater RO plants today have a second-law efficiency of only about 25-35% [1]. Novel RO configurations like batch RO can reduce the energy consumption further by closely matching the osmotic pressure of saltwater as it is concentrated, minimizing entropy generation, and reducing fouling. Efficiency-optimized coupling of renewable energy generation to highly efficient batch RO (BRO) holds the potential to cost-effectively decouple freshwater production from fossil fuel use.

Reverse Osmosis Efficiency: In 2016, energy-efficient BRO, a novel configuration of RO with lower energy requirements (Fig. 1) and higher resistance to membrane fouling, was invented by Warsinger and Tow et al. [2-4]. This grounbreaking technology won several prcies including a patent [4]. Models predict BRO can use 15% less energy for seawater desalination than continuous RO with the same membrane area [3]. Furthermore, the rapid salinity cycling of BRO systems is predicted to reduce membrane scaling, enable higher water recovery, and reduce concentrate volume [2]. In addition to improving the efficiency and fouling resistance of desalination systems, reducing the environmental impact of desalination will require the use of renewable energy which has a major benfit of not using water for cooling as any other cycle. In addition to improving the efficiency and fouling resistance of desalination systems, reducing the environmental impact of desalination will require the use of renewable energy.

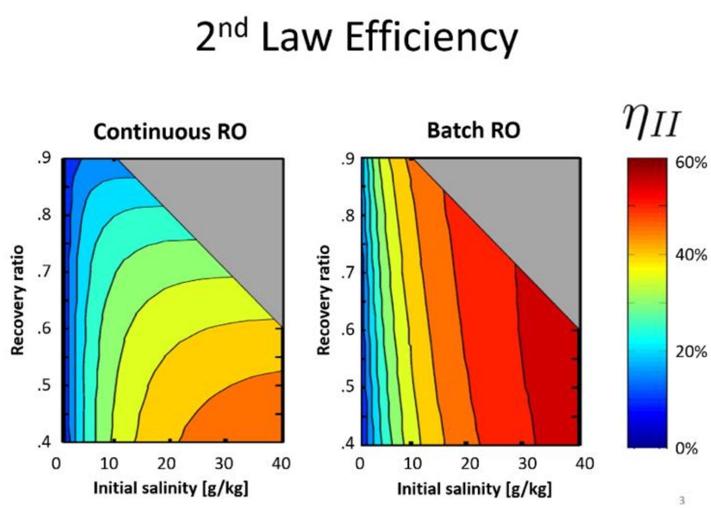


Fig. 1. Second law energy efficiency analysis comparing continuous RO to the novel proposed batch RO. Contour map shows brackish through seawater (35 g/kg) salinity. Figure from [3].

***Solar-powered Desalination*:** Solar power is a natural choice because of its wide availability and low cost. A large number of studies have examined solar powered RO, especially PV-RO, but also thermal RO with electricity producing engines [1]. The engine based processes, while less developed, show substantial promise, and have shown better net energy efficiency, as the power cycles achieve higher efficiencies (e.g. 35%) compared to the PV panels (~20%) (Table 1.). Thus effectively today, the most efficient thermal desalination process is the CSP towers ("Heliostats") in Spain which serve an electric grid having desalination plants a few dozen miles away. However, by design and cycle choice (Rankine) these systems are very limited to very large sizes (typically greater than 100 MW and depend on water for cooling), and sizes smaller than 50 MW are called "MicroCSP." However, Stirling engines placed at the focal point of solar thermal tracking dishes have shown exceptional efficiency and have been produced commercially: these dominate the "MicroCSP" market—valuable for military deployment, rural areas and developing countries. However, all these systems convert to electricity first, which adds substantial capital costs as well as moderate maintenance costs and energy losses. Furthermore, there has not yet been a solar process (even PV) driving a Batch RO process, as these batch processes are so new.

Overall, the successes and high efficiencies of the Stirling engine CSP systems indicate that the novel combination proposed here has enormous promise in terms of cost. Although solar photovoltaics are an attractive option to power electrically driven RO, the novelty of this system lies in using a Stirling engine to *directly* drive the BRO pump after a fixed speed reduction, eliminating the cost and losses involved in converting solar energy to electricity to pump work. A Stirling engine was chosen as the solar heat-to-work converter over open thermodynamic cycles such as the Rankine cycle due to its high thermal efficiency even at small scales [6].

The overarching goal of this proposal is to exceed the overall efficiency of PV-RO by using a solar Stirling engine with a concentrating dish (17-29% efficient [6]) to directly drive BRO (approximately 40% efficient for saline groundwater desalination [7]) to achieve an overall target efficiency of 10%[1] in a large-scale groundwater desalination system. As shown in Table 1, this would be the lowest-energy solar groundwater desalination system yet developed. The proposed system (Fig. 2) will test the viability of t-BRO and enable more accurate prediction of large-scale t-BRO performance.

[1] Based on assumed generator and motor efficiencies of 97%, mechanical transmission efficiency of 98%, and Stirling engine efficiency of 23%.

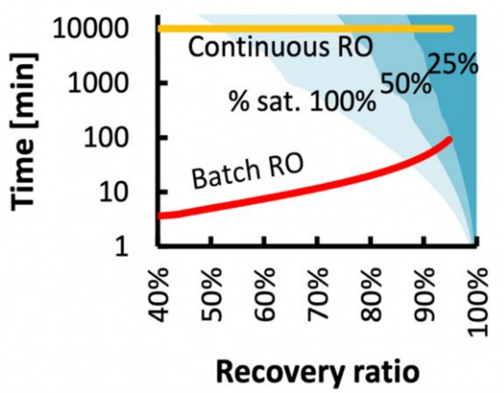


Fig. 2. Reduced salt scaling of batch RO explained: residence times for salt nuclei in batch systems (red) are very brief, while lengthy in continuous RO (orange) due to boundary layers. Batch RO reaches salt nucleation regions ($CaSO_4$, shaded) at much higher recovery ratio. From Warsinger et al.[4]

Economic Analysis:

The benefits of implementing BRO desalination translate to substantial economical benefits as well. The cost savings in the RO variant come from component innovations, increased recovery, and reduced membrane fouling, as shown in Fig. 3. Batch RO has substantial energy savings as it can ramp applied pressure to follow the osmotic pressure over time to dramatically reduce the wasted excess energy from overpressure. Additionally, because it is thermodynamically a closed system, energy is not leaving the system as pressurized brine, which removes the need for pressure recovery devices while meeting energy targets.

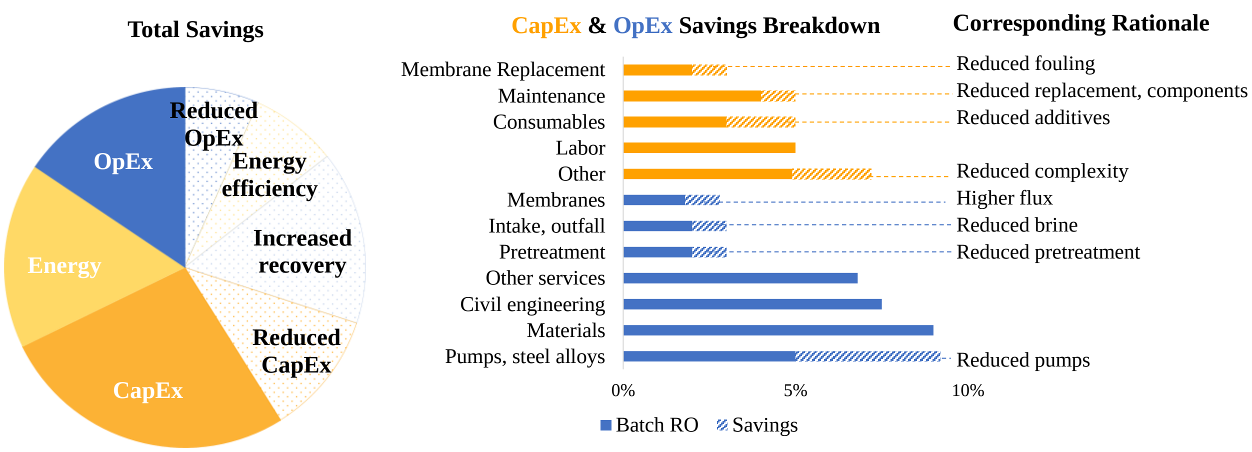


Fig. 3. Cost savings breakdown of batch RO compared to standard seawater RO, with rationale for each (right). Increased recovery (50% to 60%, enabled by reduced fouling) spreads cost over increased permeate production. RO costs are reduced from \$0.79/m^3 to \$0.45/m^3. Modified from Warsinger et al.[4]

3. Technical Approach and Project Activities

As shown in Fig. 4, the high-pressure pump shaft will be directly coupled to the Stirling engine power shaft after a rhombic drive via a single-speed gear reduction. This would be simpler, lighter and more robust than using an actively controlled multi-speed transmission. A heating loop will connect the concentrator and the heating chamber of the Stirling engine. As the concentrator has to continuously track the sun, the placement of the engine-pump assembly on a platform close to the ground facilitated by the heating loop will reduce the sprung/suspended mass and consequently vibrations.

With increase in salinity during a batch, the osmotic pressure of the recirculating brine will increase which will in turn increase the load on the engine. Since the power input to the engine is almost constant, the engine and hence the pump will slow down. This implies that flux through the membrane modules would reduce over time. Since, we would be dealing with groundwater, a drastic change in salinity and hence pump speed is not expected.

The main advantage of the high-pressure divided tank will be reduced downtime with the BRO system. During the first batch of the BRO cycle, the upper chamber of the high pressure tank will be pressurised with feed (by the high pressure pump coupled to the engine) at ambient salinity. The piston in the tank will in turn pressurise the feed in the lower chamber of the tank that had been filled in the previous batch and initiate the first batch of the cycle. The brine recirculation valve will stay shut during this time; brine recirculation due to the circulation pump and reduction of the brine circuit volume with time will cause the concentration in the lower chamber of the tank to rise. This will lead to an increase in the osmotic pressure of the brine and the pump will slow down due to increased load on the engine. The half cycle will be stopped when the desired recovery is reached. The tank will be sized so that the piston is at its lowermost position at this time, marking the end of the first batch. After depressurising the lower chamber using a pressure relief valve, the flush valve will be activated to circulate fresh feed through the brine circuit and membrane modules, expelling the high concentration brine. Once flushed, using valves, the lower chamber will be connected to the high pressure pump and pressurised with ambient salinity feed while the upper chamber will connect to the membrane modules. The piston will now move up and the feed stored in the upper chamber during the first half of the cycle will get concentrated due to brine recirculation caused by the circulation pump now connected to the upper chamber. The second half of the BRO cycle ends with the piston reaching its topmost position, followed by flushing. By using a divided tank, the downtime of the system is reduced to only the time required to flush the system which can be reduced even further by using a large volume flow rate during flusing. Fig. 4 depicts only first half of the cycle and doesn’t show the switching valves and circuit.

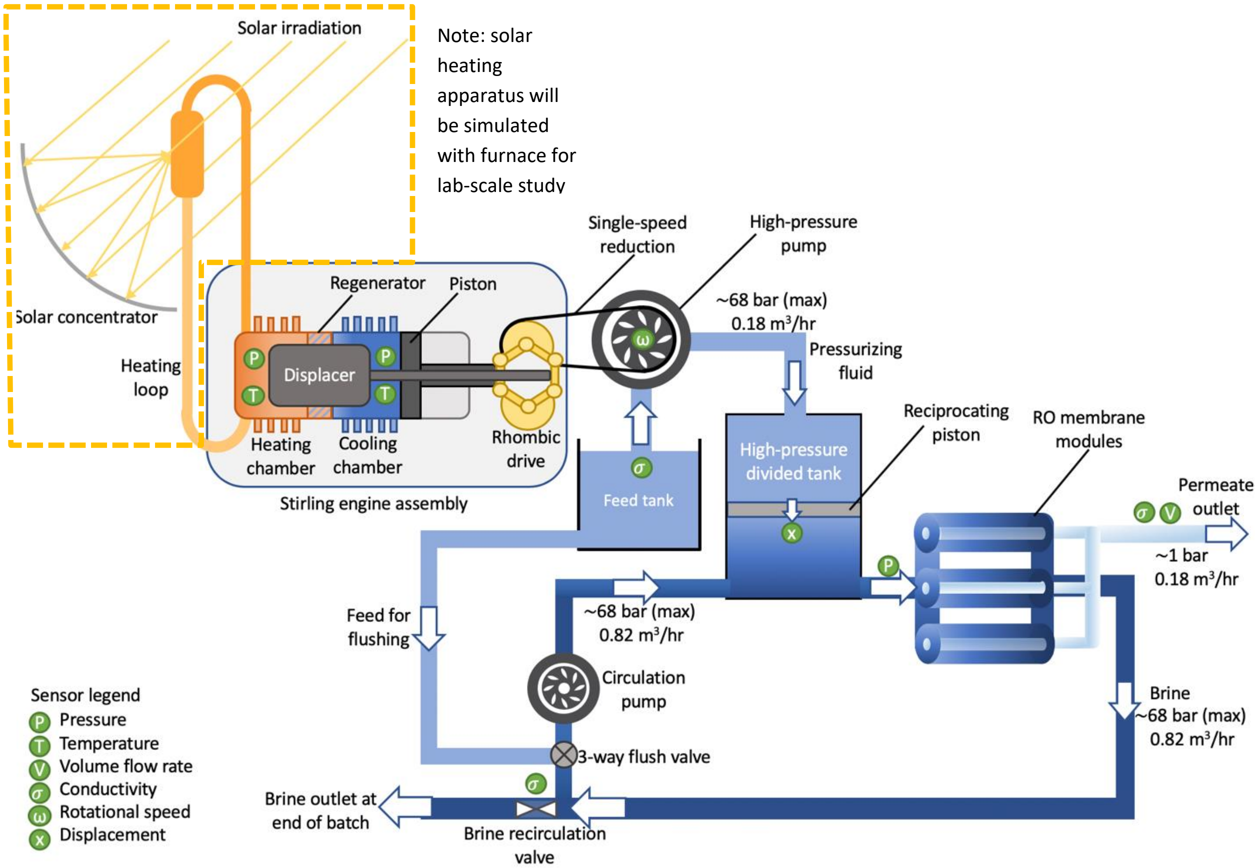


Fig. 4. The novel CSP t-BRO system combines the most efficient implementations of several technologies. A solar concentrating dish heats up a heat transfer fluid which then powers the Stirling engine, coupled through a gear reduction to the high-pressure pump for reverse osmosis. This combination avoids the expenses and losses from converting to and from electricity. The load on the engine will increase with salinity and the flow rate through the pump will decrease over time in a batch. The BRO unit (lower right) is a relatively new design that represents the highest efficiency achievable for reverse osmosis.[2] The lab-scale prototype will not yet incorporate solar heating and instead use a laboratory bench-top furnace for heating, but a future pilot-scale iteration would.

Prof. Warsinger's group has recently demonstrated energy savings with this new configuration for the BRO process incorporating a high-pressure divided tank. Fig. 5 shows a map for the specific energy consumption (SEC) for different inlet salinities and recovery ratios for 3 different reverse osmosis configurations. BRO, with an SEC less than 2 kWh/m^3, outperforms other RO configurations.

[2] Pressure is varied over time by driving permeate flux with a piston in a divided tank, which is pushed by fluid (shallow blue in Fig. 4) that is pressurized by the high-pressure pump. At the end of the stroke, the valves switch flow paths (not shown); the lower chamber gets pressurized while the upper chamber connects to the RO modules . See Refs. [3, 7] for details of energy-efficient batch RO system operation. The figure depicts only the downward motion of the piston.

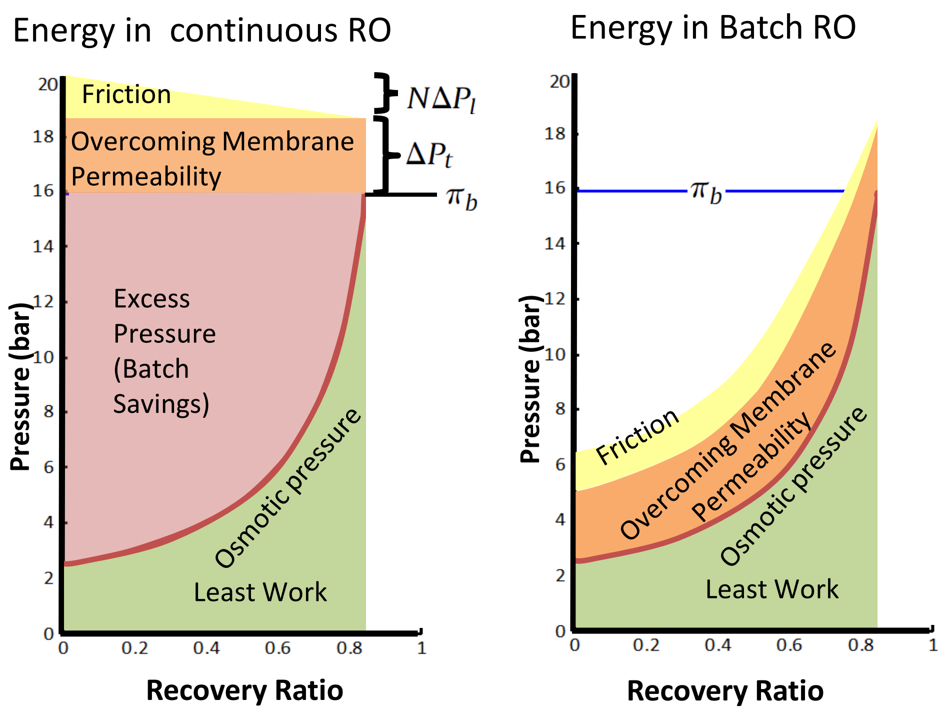


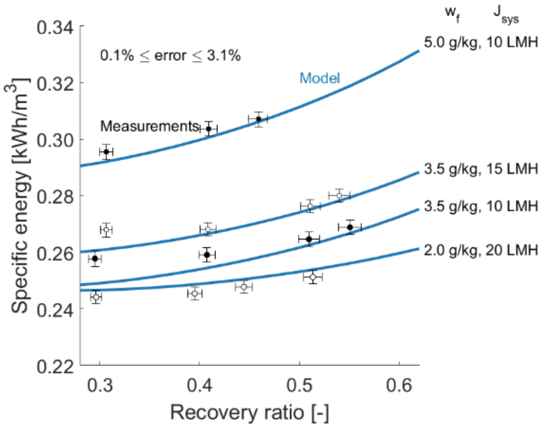
Fig. 5. Shows the applied pressure versus recovery ratio of current continuous systems versus batch RO, for brackish water concentration. All areas roughly correspond to energy, as pumping work is the volume integral of pressure. By varying the pressure over time to follow the osmotic pressure, the batch process dramatically reduces energy needs, in this case by well over 30%

Table 1. Solar energy consumption of proposed system and alternatives

Technology	Energy consumption ($kWh_{solar}/m^3_{product}$)	
	Groundwater	Seawater
t-BRO	**4**	**8**
PV-RO	7	13
CSP-MED	38	39

The applicants have demonstrated energy-efficient BRO at bench-scale [8], experimentally validated an existing model of BRO energy efficiency (see Fig. 6) and have shown that it can reduce RO energy consumption by as much as **15% for seawater, and much more for brackish water. Our overarching goal is to enable sustainable, low-cost, and high-recovery purification of both seawater and groundwater sources by developing novel processes for desalination with a viable path to market.** That said, the focus of this investigation is the efficient solar desalination of groundwater, in particular, due to the high scaling resistance of BRO. Due to the short time scale of BRO cycles and periodic brine flushing, the membranes are predicted to tolerate a higher scaling salt concentration without fouling, enabling higher recovery in desalination of saline groundwater [2].

The work will aim to understand the potential performance capabilities of thermal RO, proposed here via this dual engine. It will also aim to analyze and test the best design solutions for ultra-efficient solar thermal desalination, and support them with thermodynamic modeling.



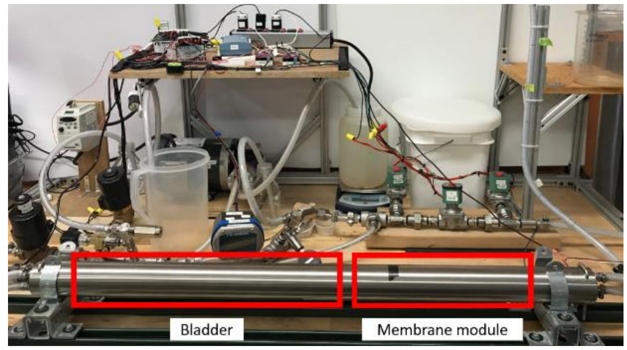


Fig. 6. Demonstrated low-energy desalination experimental data and model predictions (left) of low-salinity water with a bench-scale BRO apparatus (right) co-designed by Prof. Tow [7].

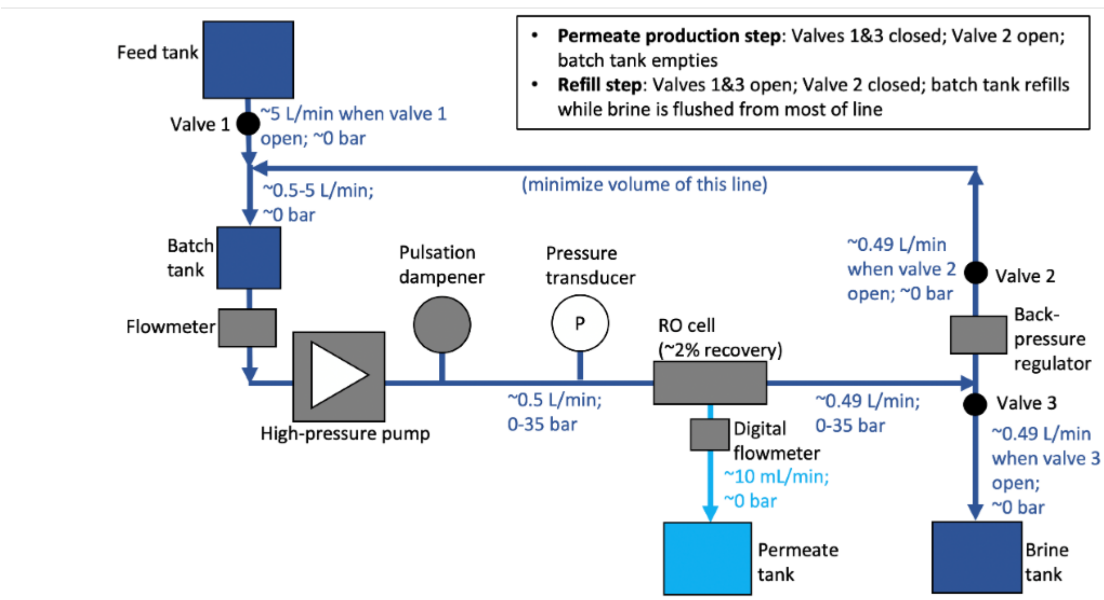


Fig. 7. Schematic of the BRO apparatus to be used for fouling studies

We will build and test a bench-scale demonstration of a thermally driven RO system, develop and validate models of its performance, and predict the energy efficiency of a full-scale t-BRO system. The RO unit will be comprised of one 40” membrane element (4” diameter), with a permeate production of approximately 1.5 gpm. More elements can be added if needed. In this stage of testing, the concentrating dish will be simulated with a heater in contact with the hot side of the Stirling engine[3]. A fan will assist with the air-cooled portion for the cold side of the Stirling engine. Initially, we will use NaCl solutions at concentrations from 1-15 g/kg and later will test with synthetic groundwater and real water from the Wabash river.

[3] We considered using a solar simulator, but the power requirements of the1 gpm desalination unit are too high. We hope to test at pilot-scale using real concentrated sunlight in the future (Castillo’s lab has capability for such setup), pending successful demonstration of the technology at bench-scale.

In terms of modelling, the applicants have validated models for transient response of RO systems. Fig. 4 also shows the various sensors that will be used to track the real time operation of the system as well as to devise active control strategies. Performance of a complete large-scale, solar-powered system will be predicted using a thermodynamic MATLAB model internally calling EES, validated with measurements from the bench-scale model and extended to include omitted components such as the solar concentrating dish and account for size-dependent component efficiencies. This modeling will enable optimization of t-BRO energy efficiency at both bench and full-scale.

We will also characterize BRO fouling performance to predict the ability of BRO to operate under supersaturated conditions to increase water recovery in groundwater desalination and/or further concentrate brine. This will be accomplished using a bench-scale batch RO apparatus at Olin College that will be optimized for scaling studies. The fouling studies will address the impact of batch operation on the nucleation time of potential scalants, the effect of batch cycle length on maximum recovery ratio, and the supersaturation levels attainable by batch RO systems for common scalants.

Mitigation of Challenges and Risks

A. Creating an energy-efficient bench-scale batch RO unit. Prof. Tow can advise the Purdue team based on her previous experience building a BRO system. We will address the issue of salt accumulation due to incomplete brine flushing identified in a recent DWPR project by optimizing the duration of flushing [9].

B. Efficiently using the shaft work of the Stirling engine to power the BRO unit's high-pressure pump with cyclically varying power requirements throughout each batch cycle (medium severity). Given its difficulty, controls that can efficiently operate the pressures for scaled up systems will be developed with advice from faculty at Purdue's Maha Fluid Power Lab. The rotating platform will rotate with the collector and avoid excessing bending and twisting of the pipes circulating heat transfer fluid between the collector and the engine. A rhombic drive and a single-speed reduction will keep the system simple and robust. Since groundwater has a relatively low osmotic pressure, the change in operating pressure during each batch cycle will be low enough that the engine torque is not expected to vary drastically. Even in the absence of a power output control mechanism/strategy, with a constant power output from the engine, the increase in load in a BRO cycle would imply a small change in engine speed. Consequently, the pump speed might still be close to the optimal pump operating speed range.

C. Disassembling an off-the-shelf Stirling engine. Prof. Warsinger's team is in talks with a Stirling engine manufacturer for assistance in disassembling a commercially available engine variant. The linear generator unit will be removed from the engine and will be replaced by a rhombic drive; a custom engine without the generator can be used if the manufacturers agree to provide one. The pressure and temperature in the engine and several key locations will be continuously monitored and shut down mechanisms will be placed to ensure safe operation with this high pressure and temperature system. In a scaled-up installation, rather than assuming a constant solar input and hence power output from the engine throughout the day, a thermal energy storage tank may be used provide a smooth heat input to the engine. This will help avoid unwanted transients on the input side to the engine. A load control system to vary the power output of the engine by varying the amount of working fluid inside it can also be developed This strategy is expected to provide a faster response (power output) as compared to varying the heat input, given the short cycle times of BRO and high thermal inertia of the engine.

D. Non off-the-shelf components: Some elements in the Solar-Thermal Batch Reverse Osmosis system need to be designed and sized specifically for the model we intent to build, as per instance the high pressure divided tank. This requisite may lead to unexpected delays in the work schedule proposed. As this issue has been faced previously, the team already has information and experience with different manufactures companies willing to build in a reasonable amount of time those specific components.

4. Research Work Plan and Schedule

Four main tasks of the project will be performed in parallel. This project will combine experimental BRO and a Stirling engine with thermodynamic modeling for building a t-BRO system with high efficiency and predicting the performance of a large-scale solar t-BRO system. Experimental data gained from Tasks 2 and 3 inform the performance and will be combined with a fully validated thermodynamic model (Task 1) in order to improve the performance of the – bench-scale system and predict the performance of a hypothetical large-scale system. In Task 4, fouling performance of BRO will be investigated in order to develop predictive models of inorganic fouling in BRO and guide operating conditions for large-scale plants. Tasks 1-3 are largely run in parallel to make the best use of down time (e.g., waiting for parts).

The work plan schedule and expected milestones are represented as a Gannt chart in Table 2.

Task 1 Thermodynamic system modeling of t-BRO (M1-M16)

Staff: Prof. Warsinger (lead advisor, 39 hr), Prof. Tow (co-advisor, 13 hr), graduate student at Purdue (modeler, 500 hr). Prof. Castillo (co-advisor, 20hrs).

Summary: Develop a comprehensive energy and fluid-flow (thermodynamic) model in MATLAB for system performance that incorporates individual components and optimizing the operational conditions of the proposed hybrid system. The model will encompass all components related to energy transfer, including fluid flows, pressure, heat, and mass transfer, to converge on a best-case system.

No apparatus is needed for this task. The only data collected will be model predictions. These include system operational parameters (temperatures, pressures, flow rates, entropy generation, etc.) that will be used to better understand and improve the experimental t-BRO apparatus as well as system performance parameters (system solar energy consumption and efficiency, recovery ratio, salt rejection, average water flux) that will be used to compare t-BRO system performance to other solar desalination systems.

Milestone 1.1: Predict efficiency of the t-BRO system as a function of engine hot-side temperature. **(M10)**

Milestone 1.2: Demonstrate a size-adjusted 2nd-law efficiency record of at least 6% for solar thermal seawater desalination with t-BRO. **(M16)**

Subtask 1.1: Model laboratory-scale system performance (M1-M4)

Model energy use and permeate quality of batch reverse osmosis system. Include entropy generation analysis. Include losses in Stirling engine, transmission, pumping, concentration polarization, viscous friction, and membrane transport. Include parasitic energy consumption of valves. Consider design choices including shaft work transmission methods and heat exchange options to converge on most efficient design for the lab scale system.

Subtask 1.2: Full-scale solar t-BRO system modeling (M4-M14)

Develop a realistic model of a full-scale, solar-powered system including solar concentration and selective solar absorber. Determine best estimate of full-scale system energy-efficiency and compare to other solar desalination options such as PV-RO and CSP-MED.

Subtask 1.3: Predict full-scale t-BRO second law efficiency (M15-M16)

Using thermodynamic model developed in Task 1, predict second law efficiency of full-scale t-BRO system.

Task 2 Developing batch reverse osmosis system (BRO) (M1-M8)

Staff: Prof. Warsinger (lead advisor, 39 hr), Prof. Tow (co-advisor, 13 hr), graduate student at Purdue (experimentalist, 650 hr)

Summary: Develop a BRO system that will be used as a hybrid system with a Stirling engine.
For this task, a BRO apparatus is needed. Data collected will include pump power, pressures, pump flow rates, solution electrical conductivity, and permeate flow rate. These data will be analyzed to determine BRO apparatus performance parameters (BRO unit energy consumption and efficiency, recovery ratio, salt rejection, average water flux) that will be used to validate baseline BRO system performance, improve BRO system performance, and compare BRO to other desalination processes.

Milestone 2.1: Demonstrate successful BRO desalination at the lab scale. **(M4)**

Milestone 2.2: Demonstrate size-adjusted 2nd-law efficiency over 40% for seawater BRO desalination. **(M8)**

Subtask 2.1: Create a lab scale BRO system (M1-M4)

Design lab scale BRO system and order components. Assemble BRO system. Validate desalination performance with pure water and NaCl solutions.

Subtask 2.2: Measure and improve second law efficiency (M5-M8)

Measure energetic performance of BRO system and vary operating conditions to improve efficiency.

Task 3 Integrating Stirling engine with BRO (M4-M18)

Staff: Prof. Warsinger (lead advisor, 58 hr), Prof. Tow (co-advisor, 32 hr), Prof. Castillo (co-advisor, 20 hr), graduate student at Purdue (experimentalist, 448 hr)

Summary: Integrate a Stirling engine with the BRO unit to achieve high second law efficiency for thermal desalination. After determining the best operational conditions by modeling, attach engine to BRO unit. Test system performance.
For this task, a Stirling engine-powered BRO apparatus is needed. Data collected will include Stirling engine top and bottom temperatures, shaft rotational speed, pressures, pump flow rates, solution electrical conductivity, permeate flow rate, and feed temperature. These data will be

analyzed to determine t-BRO performance parameters (Stirling engine efficiency, BRO unit energy consumption and efficiency in terms of sunlight, recovery ratio, salt rejection, average water flux) that will be used to determine t-BRO system performance, compare t-BRO to other desalination processes, and validate the model developed in Task 1.

As part of this task, we will write the **technical report**. Because we plan to submit at least two journal papers for peer review and present at one conference during the award period, we anticipate having plenty of material for the final report. We will report on the problem, approach and methods, experimental findings, model validation and predictions, and recommendations for future work: likely either pilot-scale testing or, if we discover unresolvable issues with t-BRO, a suggested alternate approach to efficient solar desalination.

Milestone 3.1: Desalinate water with t-BRO system. **(M19)**

Milestone 3.2: Validate model of the laboratory-scale t-BRO system. **(M21)**

Milestone 3.3: Submit paper on t-BRO performance to peer-reviewed journal. **(M23)**

Milestone 3.4: Submit final project report. **(M24)**

Subtask 3.1: Determine optimal way to power BRO with solar Stirling engine (M4-M8)
Determine type of shaft work transmission (e.g., planetary gearbox, continuously variable transmission, etc.) by modeling effect of different options with model being developed in Task 1. Determine best method of cold-side heat exchange (feed or permeate). Source Stirling engine, heat exchanger, and transmission unit for powering BRO system. Test baseline Stirling engine performance.

Subtask 3.2: Create and test t-BRO system (M9-M17)
Use a solar simulator as a source of solar concentrated energy and integrate it with Stirling engine. Integrate Solar simulator with Stirling engine and use a wide range of operational conditions (radiation flux) in order to analyze the performance of the Stirling engine. Determine the most efficient operational conditions of the integrated t-BRO system. Additionally, characterize membrane scaling on membranes from this apparatus and the one developed in Task 4 using SEM.

Subtask 3.3: Validate laboratory-scale model (M20-22)
Validate thermodynamic model of laboratory-scale system developed in Task 1.

Subtask 3.4: Report on results (M21-M24)
Submit paper(s) related to thermodynamic modeling and experimental results of the t-BRO system to peer-reviewed journals. Prepare final project report.

Task 4 Investigating fouling with a bench-scale BRO system (M1-M24)

Staff: Prof. Tow (lead advisor and experimentalist, 425 hr), undergraduate students at Olin College (experimentalists, 1600 hr in total)

Create a small bench-scale BRO system to test fouling performance, validate predictive models of inorganic fouling (scaling) in batch RO, and inform operating conditions of BRO systems. Results will be used to determine safe operating conditions for bench-scale solar thermal BRO apparatus as well as future BRO installations with any energy source at pilot- or full-scale.

For this task, an existing bench-scale RO apparatus will be upgraded to operate in batch RO mode. Data collected will include feed pressure, feed and permeate electrical conductivity, and permeate flow rate. Fouled membranes will also be removed, rinsed with ethanol, and allowed to dry before SEM analysis. Data will be collected while treating salt solutions to above saturation to determine when scaling occurs and characterize the scaling performance of batch RO systems with different cycle durations.

Milestone 4.1: Using built BRO apparatus, achieve RO permeate flux and salinity as expected with pure water and NaCl solutions. **(M12)**

Milestone 4.2: Determine maximum recovery ratio of BRO system as a function of feedwater scalant (calcium carbonate and calcium sulfate) concentration and batch cycle time. **(M21)**

Milestone 4.3: Submit paper on scaling of batch RO to peer-reviewed journal and submit final report. **(M24)**

Subtask 4.1: Design bench-scale BRO system for scaling measurement (M1-4)
Minimize system volume to enable batch cycle durations of around 20 min at 80% water recovery. This apparatus will focus on testing scaling performance and not be optimized for energy efficiency; part of the feed loop will be at atmospheric pressure.

Subtask 4.2: Build BRO system and validate its desalination performance (M5-M14)
Create flat-sheet RO cell with area around 150 cm^2. Automate batch cycling. Test desalination performance (flux and rejection) with NaCl solutions.

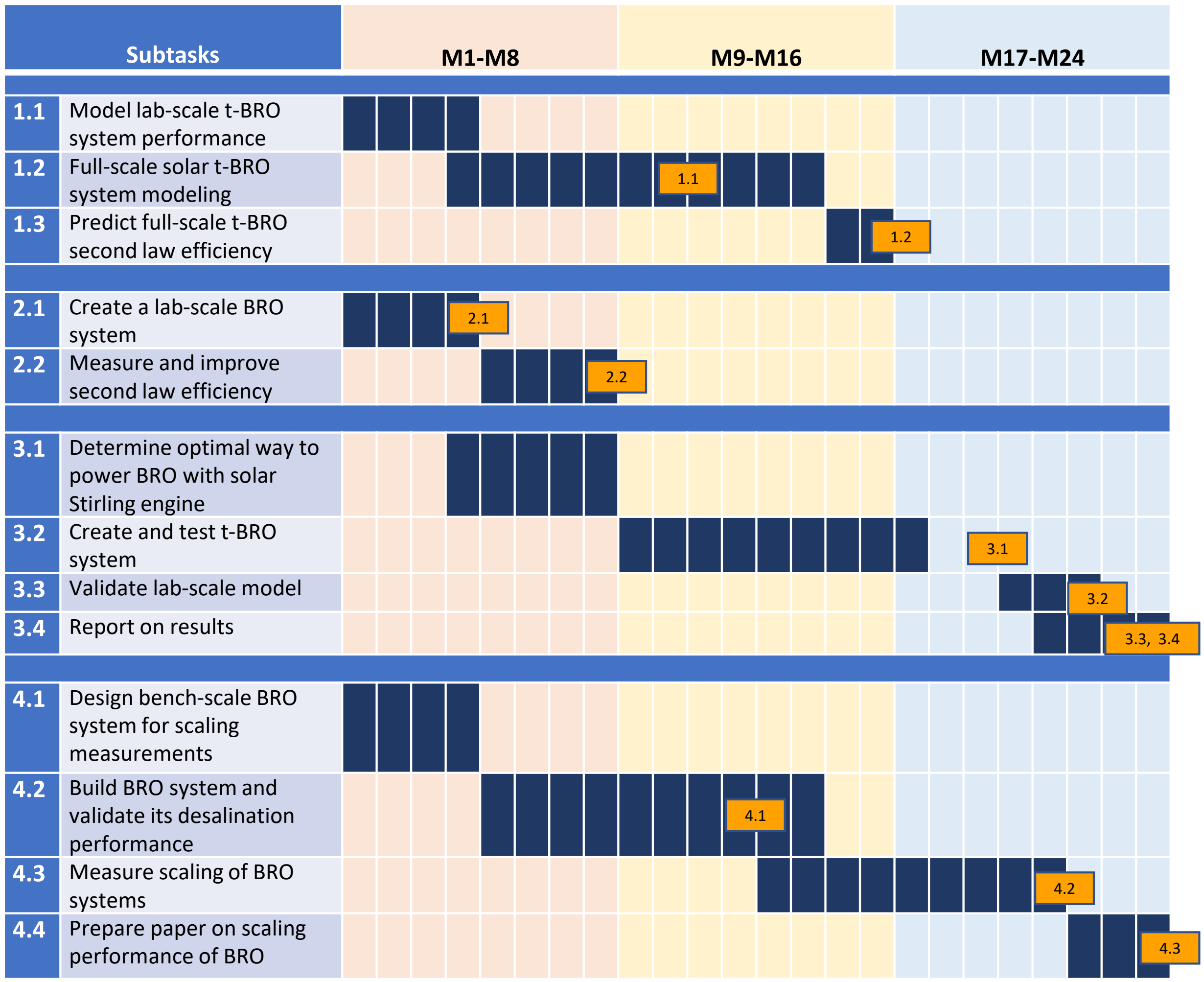
Subtask 4.3: Measure scaling performance of batch RO systems (M13-M21)
Compare onset of scaling to expected induction time with common scalants (calcium sulfate and calcium carbonate). Compute saturation index with PHREEQC. Determine maximum recovery ratio of BRO systems as a function of feedwater composition and cycle time. Compare scaling performance to model predictions. Determine safe operating conditions for solar thermal BRO apparatus and future pilot-scale and large-scale solar thermal BRO plants. Send scaled membranes to Purdue for SEM characterization.

Subtask 4.4: Prepare paper on scaling performance of batch RO for submission to a peer-reviewed journal. (M22-M24)
Report on results of Subtask 4.3.

5. Research work plan and schedule

Research activities were described in detail in Section 3. The work plan schedule is represented as a Gannt chart in Table 2.

Table 2. Work schedule



Milestone:

1.1 Predict efficiency of the t-BRO system.

1.2 Demonstrate a size-adjusted 2nd-law efficiency record of over 10% for solar thermal groundwater desalination with t-BRO.

2.1 Demonstrate successful BRO desalination at the bench-scale.

2.2 Demonstrate size-adjusted 2nd-law efficiency over 40% for BRO desalination of synthetic groundwater.

3.1 Desalinate water with t-BRO system.

3.2 Validate model of the bench-scale t-BRO system.

3.3 Submit paper on t-BRO performance to peer-reviewed journal.

3.4 Submit final project report.

4.1 Using newly built BRO apparatus, achieve RO permeate flux and salinity as expected with pure water and NaCl solutions.

4.2 Determine maximum recovery ratio of BRO system as a function of feedwater scalant concentration and batch cycle time.

4.3 Submit paper on scaling of batch RO to peer-reviewed journal.

6. Quality assurance/quality control (QA/QC)

As quality assurance (QA) and quality control (QC) are essential aspects of any laboratory testing by ensuring that the data generated during the experiments are consistent, here we discuss some of the activities to be performed in order to assure the quality and validity of the obtained results:

- Desalination performance of both BRO apparatuses will be validated using pure water, synthetic groundwater and real water from the Wabash river to test baseline permeate flux and salt rejection.
- Thermodynamic models developed will be validated by comparison with experimental results from both the BRO subsystem and the full t-BRO system.
- Inorganic scaling performance will be compared to model predictions based on the expected induction time with common scalants (calcium sulfate and calcium carbonate).
- Membranes will be checked for fouling using scanning electron microscopy (SEM).
- The collaborative nature of this project will improve quality control; teams will meet remotely over WebEx monthly to review documentation and progress.
- Findings will be submitted as papers to peer-reviewed journals and presented at conferences to solicit feedback from global experts.
- Advice and criticism will be generously provided by the Boris Liberman of IDE technologies. IDE is among the world's largest desalination firms, and they have their own BRO process (pulse-flow RO).
- The team will create benchmark procedures to test the quality of the permeate produced and the specific energy consumption in the system in order to look for statistically significant variations during different measurement periods.
- A data acquisition system together with an effective control strategy are fundamental to efficiently use the mechanical work provided by the Stirling engine and successfully control the applied pressure required in the Batch RO system according to the recirculating brine salt concentration. To procide quality assesment during the permeate production step, several sensors will be used as follows:
- **Temperature:** Temperature sensors will be placed in the stirling engine cooling and heating chamber, that way the amount of working fluid required in the engine can be control to meet the variable load requirement in the BRO process.
- **Pressure:** Pressure sensors are required in the RO membrane outlet port in the high pressure recirculating circuit, high pressure pump inlet and outlet ports in the RO system. Other than that, pressure will be measured in stirling engine cooling and heating chamber as well.
- **Flow Rate:** The flow rate needs to be measured in the high pressure pump outlet pump, in the RO membrane outlet port in the high pressure recirculating circuit and in the permeate outlet.
- **Concentration:** The concentration needs to measure to infer the salinity in the feed solution, the permeate and the recirculating brine.
- **pH:** The pH will be measured in the feed solution to protect the integrity of the RO membranes and in the permeate outlet to control its quality.
- **Displacement:** The reciprocating piston displacement in the high-pressure divided tank needs to be measured to control the start and end of the different steps in the Batch RO cycle (filling, permeate production and flushing).

7. Facilities and equipment information

The bench-scale system will be built in Renewable Energy Laboratory (Castillo's lab) and Maha at Purdue University that has more than 15,000 square feet of testing space, being the largest academic fluid power lab in the country. This lab is the ideal location to develop the project because the team will have several indispensable equipment required to successfully construct and test the apparatus as, for instance, test rigs to evaluate the performance of the pumps to be used in the apparatus. Moreover, the team will have ample computational resources provided by Purdue and for additional experiments, the team has full access to the Birck Nanotechnology Center, a state-of-the-art multidisciplinary nanotechnology research center, along with the Purdue Solar Energy Utilization Laboratory. The bench-scale system will be mounted on a trailer-skid, as shown in Fig. 9, so will return to the lab after field tests (Warsinger & Castillo have joint projects in the lab integrating wind energy & RO systems). Both applicants plan to continue to study renewably powered desalination in their respective labs, so the equipment will continue to be used (as-is or modified) for at least five years. When their useful life ends, apparatuses will be disassembled and component parts reused for other projects, donated to other labs, or disposed responsibly.

Prof. Tow has already built a bench scale BRO apparatus as shown in Fig. 6 which will be improved to make it capable of fouling studies (schematic shown in Fig. 7). Prof. Warsinger's team has experience building BRO systems, performing sizing calculations to choose flow equipment and is familiar with handling pressure vessels, membrane module, pressure relief controls, axial piston pumps and an assortment of sensors for online monitoring. The pump to be used for this bench-scale system has already been used for other BRO projects. Prof. Warsinger's team is in contact with the manufacturers of the Stirling engine to work out a way to separate the generator unit from a commercially available variant of the engine and attach a rhombic drive.

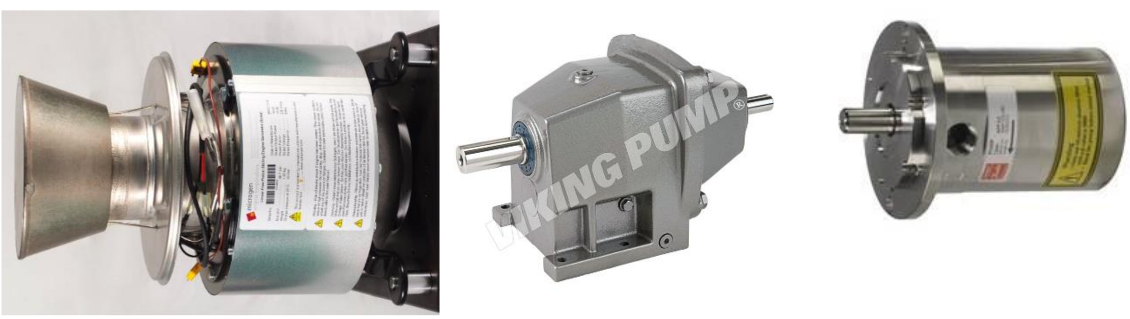


Fig. 8 Heat-to-pressure powertrain assembly, from left to right: 1 kW Microgen free-piston Stirling engine [10], Viking inline reduction gearbox [11], Danfoss 0.2-1 m^3/h axial piston pump (Danfoss part number 180B3037).

8. Environmental Impact

BRO is expected to have a higher recovery ratio compared to conventional RO, leading to lower water consumption and lower concentrate disposal volumes. The system is solar-powered, reducing emissions. It is also a goal that, through improved fouling resistance, BRO will require less dosing of pretreatment and cleaning chemicals. The project itself should create minimal environmental impact. Care will be taken to minimize the use of resources, including materials, energy, and water. Waste streams will be non-hazardous salt solutions, which will be drain-disposed. No permits are required.

9. Responses to evaluation criteria

A. ***Technical***

1. **Impact of the Proposed Work**: Given that a solar-thermal batch RO system (t-BRO) has the potential to produce 4-10× the freshwater of a CSP-MED system from the same amount of sunlight, development of t-BRO solar desalination systems could have a huge impact on renewable desalination capabilities worldwide. The proposed work is the first bench-scale demonstration of the t-BRO system, which is a necessary step toward developing solar t-BRO and enabling renewable desalination with groundbreaking efficiency.
2. **Alignment with Department Priorities and Reclamation 2019 Key Goals:** This proposal aligns with the Department's priority of "utilizing our natural resources" by creating a freshwater production system that utilizes sunlight and groundwater. As mentioned in the introduction, it is not sustainable to burn fossil fuels (a limited resource) to treat water, for which we have an unlimited need.
3. **Demonstration of Familiarity in the Field of Work**: This proposal improves significantly upon a previous submission that lacked sufficient technical detail and discussion of risks. The greatest weakness in the last submission was a largely absent description of the coupling of the Stirling engine to the high-pressure pump; we have now provided substantial detail and added a power conversion expert (Prof. Luciano Castillo) to the team to address this issue. We hope that the level of detail, combined with our qualifications, are adequate to demonstrate familiarity in the field. More information on familiarity is now included in the introduction.
4. **Relationship to DWPR Objectives:** As explained in Section 2, the proposal closely matches all sets of stakeholder objectives, following the priorities in desalination/water reuse and that are specific to the WIIN Act, including the focus on desalination and water reuse:
    a) "*Reduce energy consumption…of desalination*" By using the most efficient desalination process, and aiming to achieve the most efficient thermal desalination.
    b) *"Reduce the environmental impacts of seawater desalination"* By achieving higher recovery and using solar power
    c) *"Improve existing reverse osmosis and membrane technology"* By proposing a new way to power RO, with thermal energy
    d) ***"****Carry out…applied research on next generation desalination technologies, including… renewable energy-powered desalination systems that could significantly reduce desalination costs"* By Using solar power, and design driven by economic analysis (Fig. 3)
    e) *"Develop and promote innovative desalination technologies, including concentrate management"* By testing/demonstrating the ability of BRO to concentrate brine to supersaturated conditions without membrane scaling*)*

5. **Readiness level:** The team and technology are at an ideal readiness: the team (Tow) has validated bench-scale BRO (see Fig. 6), and Warsinger has recently built a pilot-scale conventional RO unit with solar photovoltaic power (Fig. 9) that is available for use in this study. Tow has built multiple bench-scale RO units for investigating membrane fouling, including one that is available for use in this study and will be converted to batch RO. Warsinger and Castillo have been working on directly coupling hydraulic wind power (the first hydraulic wind turbine in USA) to RO pumps, which faces more design challenges than the proposed. Additionally, for integration with solar power, the investigators' backgrounds in mechanical engineering and teaching Heat Transfer (and PhD training in MIT's Rohsenow Kendall Heat Transfer Laboratory) prepare them for the associated challenges. The group is well prepared to do Stirling engines, as the Warsinger Lab recently built one from scratch for thermal disinfection, although the aim here is to purchase one. Moreover, Stirling engines are extensively used in CSP applications owing to their high thermodynamic efficiency and relatively simple construction. Given the scale of the CSP farms, scaling up the proposed t-BRO system is a feasible objective. Constant speed operation of the engine and the pump will help reduce inefficiencies at sub-optimal operating points.

Fig. 9 Solar-powered RO prototype previously built at Purdue University

   Prof. Warsinger is in talks with Microgen Engine Corporation, who are well known for their versatile Stirling engines capable of handling different kinds of heat sources. A 1 kW engine is commercially available which can be easily modified and coupled to the high-pressure pump. Prof. Warsinger has experience building RO skids which can be powered by renewable and intermittent energy sources like wind and solar PV. The authors have four journal publications, three conference publications, one patent, and one patent application on batch RO, comprising substantial modeling and experimental work.

   Warsinger already has a pilot-scale RO system, which will be modified to create the thermally-powered system, and Tow has a bench-scale RO fouling test apparatus that will be modified to operate in batch mode. Furthermore, the facilities available at the Birck Nanotechnology Center and Maha Fluid Power Research Center at Purdue are adequate to support the development of the t-BRO apparatus.

6. **Novelty of approach to work:** Energy-efficient BRO was invented by Prof. Warsinger (PI) and Prof. Tow (co-investigator) in 2015. The further novelty of this proposal is integrating a BRO system with a solar-powered Stirling engine to eliminate inefficient energy conversions and create a highly efficient renewably-powered water desalination

system. This will be the first fully thermally-powered RO process without unneeded electrical components, a novel concept with applications in off-grid and renewable desalination.

B. ***Managerial***

1. **Qualifications of team**
    a. **Team has adequate qualifications and experience**: Prof. Warsinger and Prof. Tow both did their doctoral research on energy efficiency and fouling in desalination and have been in the field for more than six years. Additionally, they are both active members of the AWWA Membrane Technology Research Committee, of which Prof. Tow is chair, and thus are familiar with the current state of research in membrane-based desalination. They have received awards for their work on batch RO, including Reclamation's More Water, Less Concentrate Challenge (2017). They have built laboratory and pilot-scale desalination apparatuses before and are familiar with the associated challenges. The team members are also well prepared to handle the thermal aspects of this project: they regularly teach courses in heat transfer; they have both built thermal desalination systems; and, combined, they have about 50 papers and patents related to thermal desalination or Batch RO.
    b. **Team expertise is leveraged by global experts outside the U.S.:** Our primary project advisor is the CTO of the international (Israeli) firm IDE technologies, Dr. Boris Liberman. We are also advising collaboration projects on batch RO in other labs, such as in MIT and abroad in Singapore.
2. **Non-Federal Cost Share**: Of the total budget of $513,898, we offer $263,898 as cost share (51.3%).
3. **Adequacy, Completeness, and Realism of the Schedule:** The project schedule is based on previous experience with similar projects. Phase durations and milestones are designed to motivate diligent work and yet allow for the possibility of occasional setbacks. Available facilities (Birck Nanotechnology Center and Maha Fluid Power Research Center at Purdue University) as well as the existing RO skid in Prof. Warsinger's lab will support timely progress.

Conflict of Interest Declaration:

The team members declare no conflict of interest. While the team has patents on related technologies, these patents follow normal rules for academic institutions and present no issue.

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