Advanced, Energy-Efficient Hybrid Membrane System for Industrial Water Reuse

DOE Cooperative Agreement No. DE-EE0005758

RTI International, Duke University, and Veolia Water Technologies, Inc.

Project Period: September 1, 2012 to December 30, 2016

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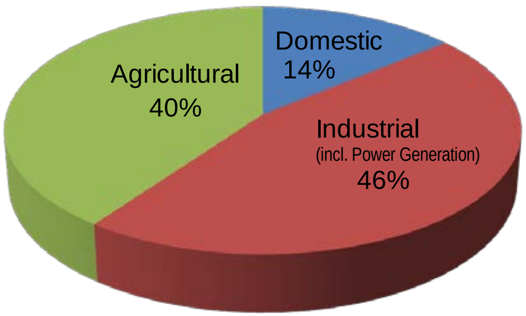
Project Objective

- What are you trying to do?
  - Develop integrated FO-MD technology as a lower-cost option for treating industrial wastewaters to reduce freshwater withdrawal and treatment energy consumption
    - Cost-effectively enable at least 50% water reuse (recovery) efficiency near term toward Zero-Liquid Discharge
    - Improve energy efficiency of industrial wastewater treatment
- What is the problem?
  - Heavy water utilization footprint of U.S. industrial sector
    - Not sustainable (limited resources, regulatory pressures)
  - Current RO Technology is not capable of producing clean water if feedwater TDS level exceeds 50,000-60,000 ppm.
  - There has not been any new technology developed for high-TDS w

Freshwater Withdrawals in the U.S. by Sector (2005)



Total = 478.4 km^3/yr

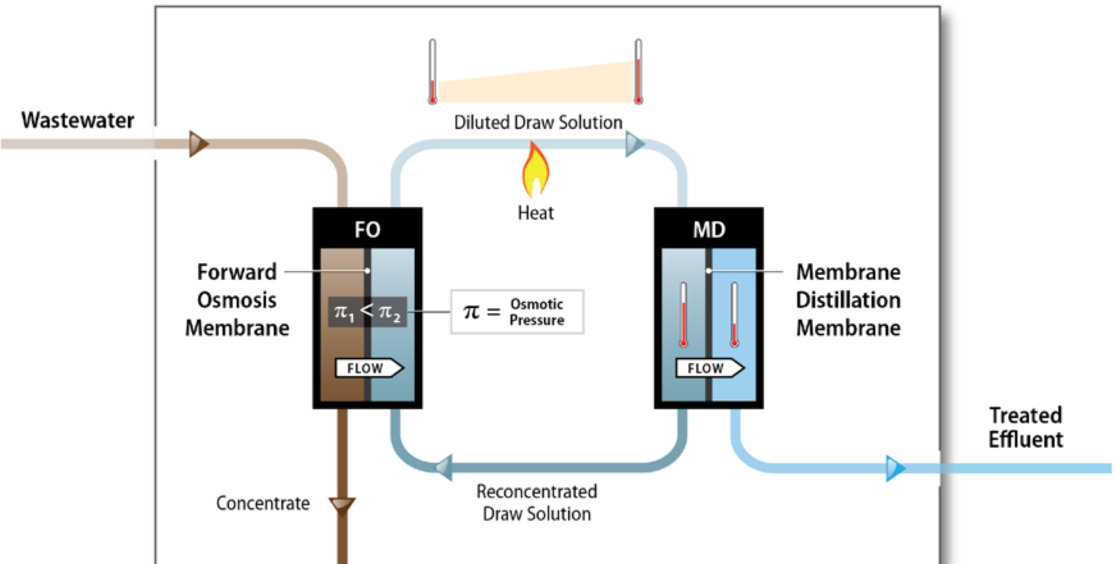
Source: U.S. CIA World Factbook

- Why is it difficult?
  - RO is generally a low-energy desalination method compared to thermal processes (MED, MSF, and Evaporator). However, at high feed TDS levels, RO cannot handle the water, while thermal processes take a significant amount of electrical energy.

Technical Innovation

- How is it done today, and what are the limits of current practice?
  - Up to 60,000 ppm TDS feed water (e.g., seawater in the Middle East) can be treated by RO
  - Higher than 60,000 ppm TDS requires thermal evaporator, which is very expensive to construct due to the high cost of exotic alloys needed as corrosion- and temperature-resistant materials of construction
- What's new in your approach, and why do you think it will be successful?
  - Utilization of waste heat, instead of electricity, for the major part of the energy required
  - Use of plastic materials instead of high alloys

Technical Innovation



- Beneficial utilization of waste heat
- Synergistic coupling of FO (forward osmosis) and MD (membrane distillation)
  - FO (osmotically driven process): Pretreatment for MD
  - MD (thermally driven process): Regeneration of high-osmotic FO draw solution
- Low-pressure operation
  - Reduced energy requirements
- High water recovery/reuse potential
- Broad applicability to different industries

Technical Approach

- What is the technical approach for the project?
  - Forward Osmosis (FO) uses salinity gradient as the driving force for water transport, so that the water is collected without energy input.
    - Current practice uses high hydraulic pressure to filter only water through semi-permeable RO membrane.
  - Membrane Distillation (MD) uses low-grade waste heat and mostly plastic materials of construction.
    - Current practice is to use thermal evaporator that is made of high alloys due to corrosion at high temperatures.
    - High energy consumption is due to high osmotic pressure of highly saline water.

  - Potential project risks and unknowns:
    - More effective heat integration & management strategies for MD process are needed.
    - Both FO and MD membranes and membrane modules need to be further developed for this process to be successful.
    - Development and manufacturing of new membrane and module types for high-TDS applications has been led by European and Asian firms.

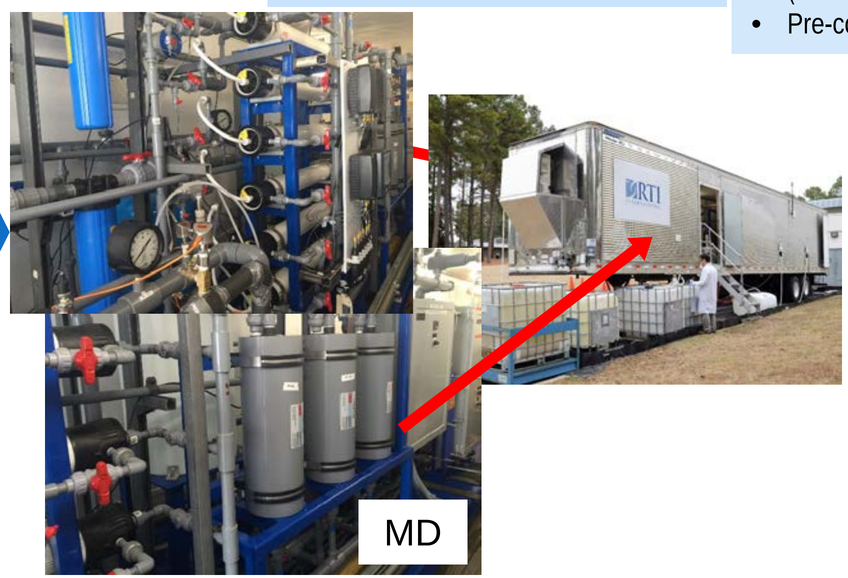
Technical Approach

Strong, Multidisciplinary Project Team:

- Duke: Basic membrane properties research, and modeling approach of the system
- RTI: Overall process concept and design. Pilot design and operation.
- Veolia: One of the largest water and desalination companies in the world. Advice on field testing

Transition (beyond DOE assistance) – Updated Roadmap

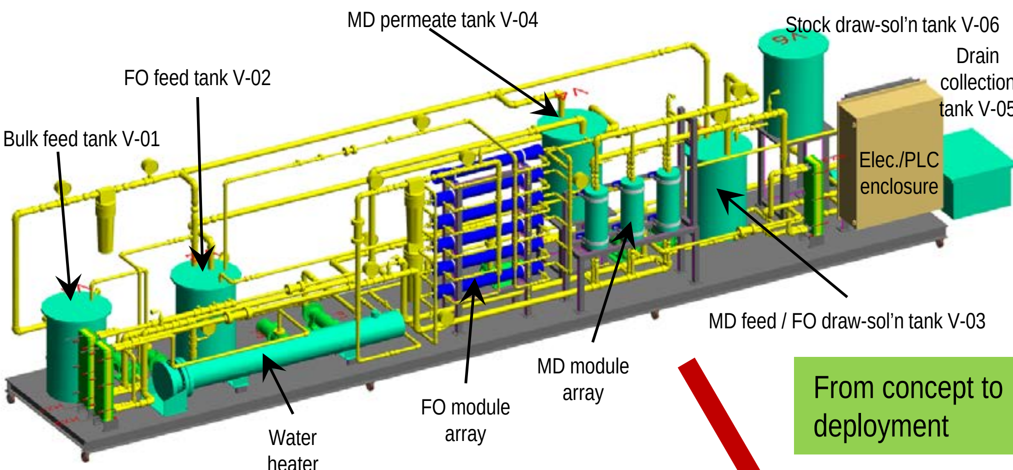
	Previous Work	Current Project: RTI / DOE-AMO (Partners: Veolia, Duke University)		Future Development/Sustainment	
Yr	→**2011**	2012-14	2015-2016	2016-2019	2019+
TRL	2-3	3-5	5-6	7-8	9
	Proof-of-Concept / Feasibility	<u>Laboratory Validation</u> ✓ Membrane screening & evaluation ✓ Process development, modeling, & integration ✓ Bench integrated system (25-gpd) testing with real wastewaters	<u>Relevant Environment Testing</u> ✓ Fabrication of field, pilot-scale testing skid (500-gpd) ✓ Installation & commissioning of pilot-scale testing skid ✓ Continuous, extended pilot-scale testing with real wastewater ✓ Final techno-economic assessment	• Membrane & module engineering improvements / optimization to increase process economic competitiveness & market relevance • Membrane / Module manufacturing • Advanced process heat (energy) integration design • Field process operational data (≥ 6 mos.) • Pre-commercial demonstration	Deployment



- Potential End Users: Membrane manufacturers, System integrators, Engineering firms, Utilities.
- Commercial Partners will expedite the acceptance of the new technology in the market.

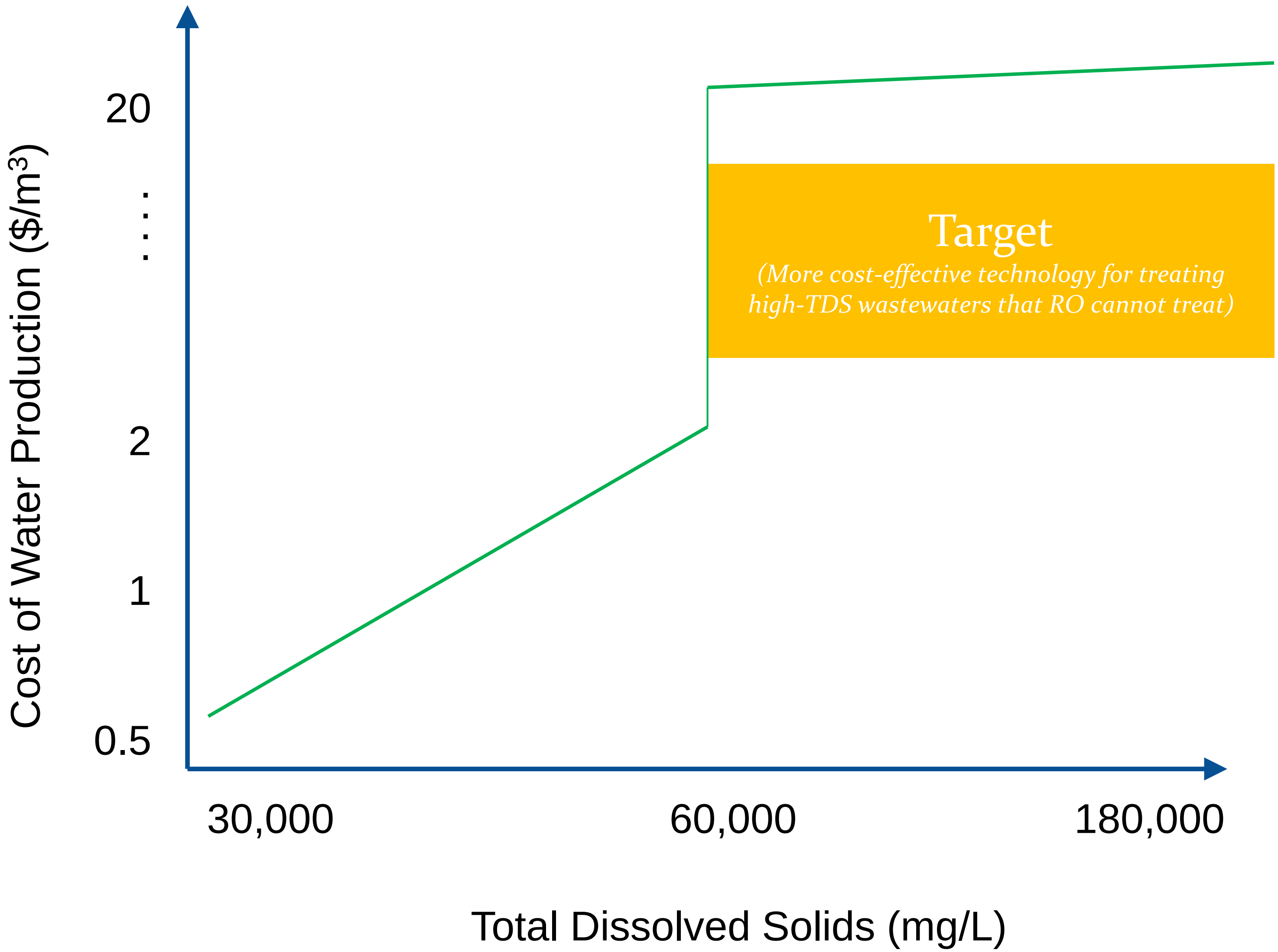
Pilot Testing

500-GPD pilot-scale FO-MD test skid and laboratory space in the mobile trailer for on-site testing.



From concept to deployment

Measure of Success



Project Management & Budget

- **Project Duration**: 52 mos. (4.33 yrs.)

Total Project Budget	
DOE Investment	$4,800,000 [80%]
Cost Share	$1,200,000 [20%]
Project Total	$6,000,000

Project Task Structure (Simplified)
1 – MD membrane development
2 – FO membrane process evaluation and optimization
3 – Bench, integrated FO/MD System performance testing
4 – Hybrid process model development and validation
5 – Field demonstration of prototype, integrated system
6 – Hybrid process design integration/Techno-economic analysis

	Status	Milestones
BP1 (15 mos.)	✓	Q3 – Successful hydrophobic surface modification of ceramic MD membranes
	✓	Q5 – Bench-scale, integrated FO/MD system design
	✓	– **Optimized FO membrane process with FO draw solution formulation(s)** ***[Go/No-Go]***
	✓	– **Preliminary techno-economic and environmental analysis** ***[Go/No-Go]***
BP2 (19 mos.)	✓	Q6 – Preliminary draft engineering design package for prototype, integrated FO/MD unit
	✓	Q7 – **Selection of at least one MD membrane having >95% rejection of dissolved solids in complex wastewater feeds** ***[Go/No-Go]***
	✓	Q8 – **Fully operational bench, integrated FO/MD test system (25-gpd)** ***[Go/No-Go]***
	✓	Q9 – Development of hierarchal, omniphobic surface for MD membranes
	✓	– **Hybrid FO/MD process model validation** ***[Go/No-Go]***
	✓	Q10 – **Selection of host test site** ***[Go/No-Go]***
	✓	– Final engineering design package for field prototype, integrated FO/MD unit
BP3 (18 mos.)	✓	Q12 – Field prototype, integrated system (500-gpd) installation/ commissioning
	✓	Q14 – Hybrid FO/MD process modeling tool fully validated with field data
	✓	Q15 – Field-testing of prototype, integrated system
	✓	Q16 – Final techno-economic and environmental analysis

Results and Accomplishments

Project Status / Accomplishments

- Successful commissioning and operation (15 weeks) of pilot-scale (~500-gal/day nominal), integrated FO-MD system with real wastewater from an oil production facility
- Various feed TDS conditions were tested (27,700/57,000/86,000/190,500 ppm)
- 5 weeks continuous operation at 130,000-140,000 ppm feed TDS
- More than 99% rejection of TDS
- More than 90% rejection of oil & grease and SVOC
- No membrane or module degradation during long-term pilot operation at high VOC concentration
- Completion of final techno-economic analysis using the pilot operational data

Required Future Work

- Long-term (> 6 mos.) MD and FO process operational data obtained on treatment of real wastewaters
- MD membranes made from lower-thermal conductivity materials
- Advanced membrane module engineering for more efficient mass and energy management (higher water flux & recovery)
- System integration strategies to improve overall process energy management [e.g., eductor using plant steam, water, etc. to create permeate-side vacuum]

Technoeconomic Summary for nth Plant (~4.5 MGD)

HIGH-TDS CASE (59,442 mg/L)				
Metric	FO-MD—Original Projection	500 gpd Pilot Values	FO-MD No recovery	FO-MD w/Heat Recovery (40%)
Water recovery (%)	80	N/A	80	80
Total capital cost ($MM)	18.9	N/A	80	80
Annual operational cost ($MM)	2.49	N/A	79	52
Electrical energy (kWh_e/m^3)	0.44	64	4.7	4.7
Heat energy (kWh_t/m^3)	10	600	900	550
Total water cost [TWC] ($/m³)	**0.75**	**N/A**	14.53	9.06
Total water cost [TWC] ($/bbl)	**0.12**	**N/A**	**2.31**	**1.44**

Current development stage may provide savings for water with high disposal costs.

Typical Costs for Disposal of Produced Waters (incl. transportation)

•California/Colorado/Wyoming/Texas - $0.15 to $0.60/barrel

•Oklahoma/Arkansas - $0.25 to $2.00/barrel

•Pennsylvania/West Virginia - $5 to $12/barrel