

Low-Energy, Low-Cost Drip Irrigation and Desalination: Innovations from the MIT GEAR Lab

Amos G. Winter, V, PhD

Ratan N. Tata Associate Professor of Mechanical Engineering
 Director, Global Engineering and Research (GEAR) Laboratory
 Massachusetts Institute of Technology
<http://gear.mit.edu/>

The Global Engineering and Research (GEAR) Laboratory (<http://gear.mit.edu/>) characterizes the unique technical and socioeconomic constraints of emerging markets, then combines these insights with engineering science and product design to create high-performance, low-cost, globally-relevant technologies. This talk will focus on GEAR Lab's innovations in water technologies: drip irrigation systems that require one-half the pumping power as conventional technology, lowering the capital cost of off-grid systems by up to 40%; and innovations in electro dialysis (ED) desalination that include photovoltaic (PV)-powered systems that are 40% less expensive than current technology, and ED stack designs which cut capital cost or production time by more than 50%. In addition to advancing the science and design knowledge in these areas, these projects have manifested in new engineering hardware and field tests with target stakeholders. Furthermore, by providing high-value, low-cost solutions, each project has become a "reverse innovation", with variants of the technology now transferring to global markets.

Low-power drip irrigation

Drip irrigation is a means of dripping water directly onto the root zone of crops. It can produce up to 90% more crops than rain-fed irrigation, and reduce water consumption by 70% compared to conventional flood irrigation [1, 2, 3]. Irrigation is the highest impact development intervention for the 500 million poor farmers throughout the developing world, enabling them to grow more and higher-value crops to rise out of poverty [4]. Most of these farmers live without access to grid electricity, and the major barrier to engaging them is the cost of solar- or diesel-powered drip irrigation systems. **We have designed drip emitters that operate at 1/7 the pressure of existing products, which can cut the overall pressure, pumping power, and energy usage of a drip system by 50% (Fig. 1), and the capital cost of a solar-powered drip system by 40%** [5]. This innovation resulted from a full mathematical characterization of the coupled fluid-solid mechanics within on-line silicone diaphragm pressure compensated drip emitters [6], then using this theory with a genetic algorithm to optimize the internal geometry of the dripper for low operating pressure (Figs. 1A-C) [5]. To our knowledge, this is the first fully parametric articulation of this technology, which was first invented in 1947 [7]. The drippers shown in Fig. 1A were successfully field tested at nine sites throughout Jordan and Morocco over the past year under a USAID-sponsored project. **Compared to commercially available products used as controls, our drippers reduced hydraulic pumping power by an average of 48% while maintaining adequate water emission uniformity per industry standards [8].** Jain Irrigation, the second largest drip irrigation firm in the world and a sponsor of this research, is pursuing a license for the technology. In the next 1.5 years, we will test fully integrated and cost-optimized PV-powered drip irrigation systems, which will leverage our recent insights into parametrically characterizing the behavior of in-line drip emitters [9], the variant of drippers most commonly used in agriculture.

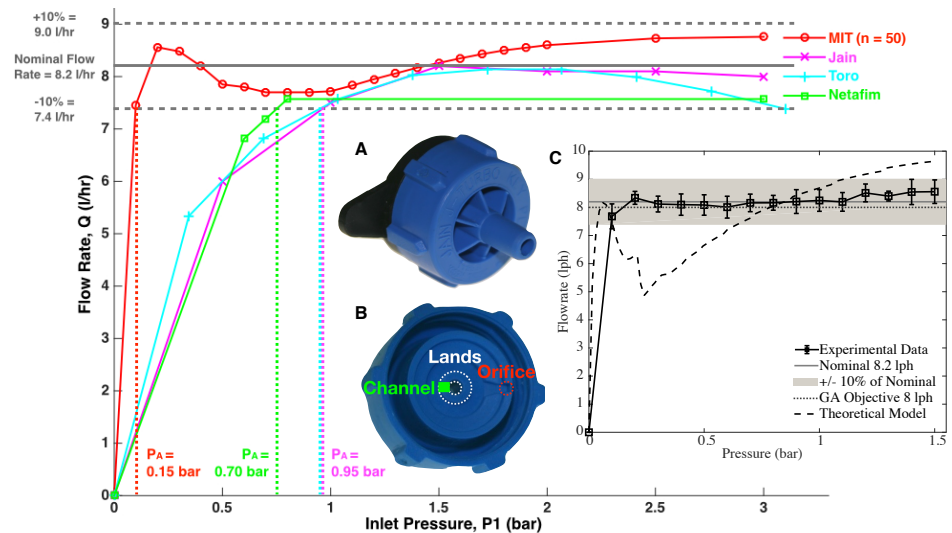


Figure 1: Low-pressure drip emitters. Plot shows the activation pressure (minimum pressure to deliver the rated flow rate) of our 8 lph on-line drip emitter is up to 7X lower than competing products. A) The MIT emitter is made exactly the same way as existing products and does not cost more. B) Flow control features optimized using a genetic algorithm with C) showing predicted versus measured performance.

The Inter-American Development Bank is currently funding us to adapt our drippers to gravity-fed irrigation systems in the mountains of Bolivia.

Low-cost brackish water desalination with electro dialysis

Given the most prevalent contaminant of groundwater in India is salt, groundwater resources are severely stressed, and most rural communities have unreliable or no grid access, **we elucidated a disruptive market opportunity for photovoltaic-powered electro dialysis (PV-ED) desalination** [10]. Compared to reverse osmosis (RO), which is currently used in village-scale desalination plants in India, ED requires half the energy (and thus half the capital cost of a PV system) and can reduce water wastage from 60% to <10%. Using these insights, we constructed a full-scale, 10 m³/day PV-ED system [11] that won the 2015 USAID Desal Prize, an international competition to create off-grid brackish water solutions. This success has led to two follow-on field pilots in India and one in Gaza (Figs. 2A and B). Building full-scale systems has given my group insights into pain points where cost and efficiency can be improved. In collaboration with Prof. Tonio Buonassisi's MIT PV Lab, **we codified how the PV and ED subsystems can be co-optimized to reduce system capital cost by 40% compared to current design practice** [12]. These savings primarily result from running the system in time-variant behavior, whereby we overproduce water during sunnier days to use during cloudy days, effectively storing energy in water tanks rather than batteries [13]. Tata Projects, an Indian infrastructure firm that has installed 2000+ village-scale desalination systems, is funding this work to create clean water solutions for their off-grid customers.

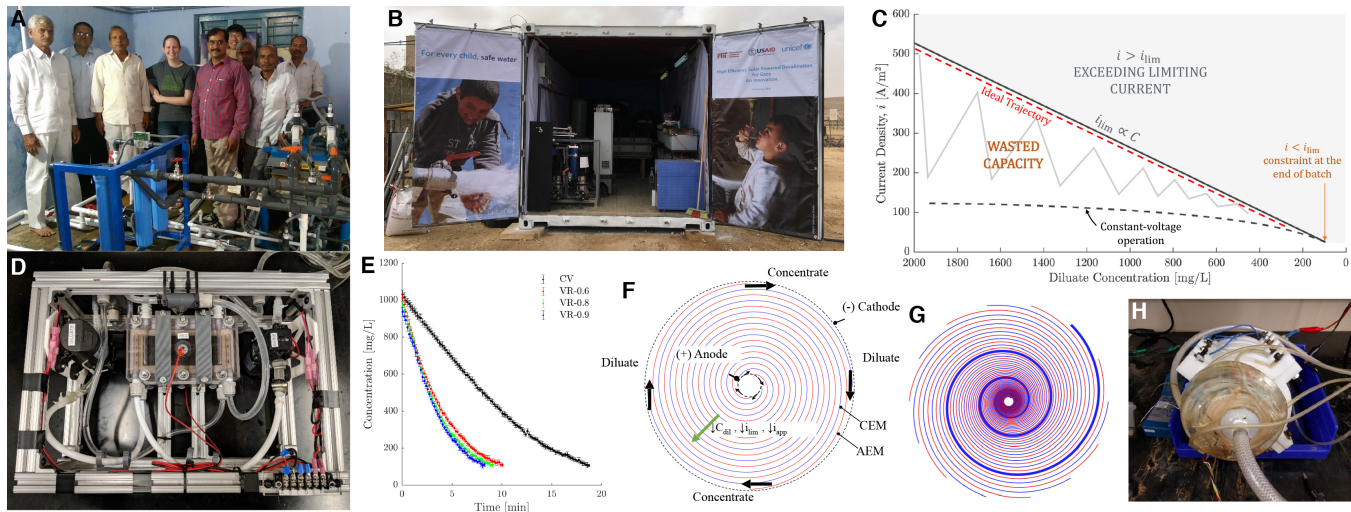


Figure 2: Electrodialysis (ED) desalination innovations. A) Photovoltaic (PV)-powered ED pilot system in Chelluru, India and B) Israel (before shipment to Gaza). C) Insight into wasted capacity of batch ED systems that run at constant voltage, which are sized so applied current density (black dashed line) only hits the limiting current density (i_{lim} , which is proportional to concentration C , solid black line) at the end of the batch. Current density $i = \frac{\text{current}}{\text{membrane area}}$. Using variable voltage ED, the system can apply a current density at limiting current density through the entire batch (red dashed line), maximizing ion transfer rate. D) Our first variable voltage ED system, sized for domestic use, E) showing up to a 90% higher production rate than the same system running at constant voltage (CV). Voltage regulation ratio is $VR = \frac{i}{i_{lim}}$. F) Spiral ED stack architecture, where water flows from the inside out and the geometry of the spiral naturally increases membrane area in successive layers such that applied current density decreases with concentration and limiting current density. G) Ideal, asymmetric spiral geometry maintains applied current density at limiting in each layer. H) Spiral ED stack proof-of-physics prototype.

The primary cost driver in a PV-ED system is the electro dialysis “stack”, composed of a series of ion-exchange membranes between which water flows. Electrodes which clamp the stack of membranes apply a voltage to draw ions out of the product water stream. My group articulated the fundamental parametric relationships behind ED electrical and hydraulic pumping behavior to create a full operational energy model [14]. These insights have led to major innovations in ED stack design and operation to reduce cost. We have generated the design theory for how to size and configure ED stacks for minimum capital and/or total costs for both small- and large-scale applications [15, 16]. Furthermore, our insights into ED behavior have led to creating actively-controlled, variable voltage ED stacks that optimally utilize membrane area and extract ions at the maximum possible rate (Fig 2C-E) [17]. **Variable voltage ED can more than double the production rate of a stack for a given membrane area, or correspondingly reduce the capital cost of the stack compared to existing products (by 69% for Indian**

village-scale applications). We have also invented a novel spiral-shaped ED stack architecture (Fig. 2F and G) which geometrically controls ion flow to maximally utilize membrane area like voltage control, but in a constant voltage, continuous-flow system; we have experimentally demonstrated (Fig. 2H) that our spiral ED stack theory is accurate to within 10% [18]. We are currently working with a leading manufacturer of ED systems to pursue tech transfer opportunities for our design theory and novel ED stack architectures for home, village, and industrial-scale desalination applications.

References

- [1] Mazher Iqbal, Fayyaz-Ul-Hassan Sahi, Tamoor Hussain, Nasrullah Khan Aadal, Muhammad Tariq Azeem, and Muhammad Tariq. Evaluation Of Comparative Water Use Efficiency Of Furrow And Drip Irrigation Systems For Off-Season Vegetables Under Plastic Tunnel. *International Journal of Agriculture and Crop Sciences*, 7(4):185–190, 2014.
- [2] Regassa E. Namara, Bhawana Upadhyay, and R. K. Nagar. Research Report 93: Adoption and Impacts of Microirrigation Technologies Empirical Results from Selected Localities of Maharashtra and Gujarat States of India. Technical report, 2005.
- [3] Kamil Nkya, Amana Mbowe, and Joachim H J R Makoi. Low -Cost Irrigation Technology, in the Context of Sustainable Land Management and Adaptation to Climate Change in the Kilimanjaro Region. *Journal of Environment and Earth Science*, 5(7):45–56, 2015.
- [4] Paul Polak. *Out of Poverty: What Works When Traditional Approaches Fail*. Berrett-Koehler, 2009.
- [5] Pulkit Shamsbery and Amos G Winter. Shape and form optimization of on-line pressure-compensating drip emitters to achieve lower activation pressure. *Journal of Mechanical Design*, 140(3):035001, 2018.
- [6] Pulkit Shamsbery, Ruo-Qian Wang, Davis V Tran, et al. Modeling the future of irrigation: A parametric description of pressure compensating drip irrigation emitter performance. *PloS one*, 12(4), 2017.
- [7] Wesley G Miller. Flow control device, 1949. US Patent 2,460,647.
- [8] J. Sokol, S. Amrose, E. Brownell, V. Nangia, S. Talozi, and A.G. Winter V. Field performance of low pressure drip irrigation emitters. *In Preparation*.
- [9] Jaya Narain and Amos G. Winter V. A hybrid computational and analytical model of inline drip emitters. *In Preparation*.
- [10] Natasha C. Wright and Amos G. Winter V. Justification for community-scale photovoltaic-powered electro-dialysis desalination systems for inland rural villages in india. *Desalination*, 352:82–91, 2014.
- [11] N.C. Wright, G.D. Van de Zande, and A.G. Winter V. Design of a village-scale pv powered electro-dialysis reversal system for brackish water desalination in india. In *The International Desalination Association World Congress on Desalination and Water Reuse*, number IDA15WC-Wright 51715, San Diego, CA, September 2015.
- [12] David W. Bian, Sterling M. Watson, Natasha C. Wright, Sahil R. Shah, Tonio Buonassisi, Devarajan Ramanujan, Ian M. Peters, and Amos G. Winter V. Optimization and design of a low-cost, village-scale, photovoltaic-powered, electro-dialysis reversal desalination system for rural india. *In Review*.
- [13] Sterling Watson, David Bian, Nasim Sahraei, Amos G Winter, Tonio Buonassisi, and Ian Marius Peters. Advantages of operation flexibility and load sizing for pv-powered system design. *Solar Energy*, 162:132–139, 2018.
- [14] Natasha C. Wright, Sahil R. Shah, Susan E. Amrose, and Amos G. Winter V. A robust model of brackish water electro-dialysis desalination with experimental comparison at different size scales. *Desalination (Accepted)*.
- [15] Sahil R. Shah, Natasha C. Wright, Patrick Nepsky, and Amos G. Winter V. Cost-optimal design of a batch electro-dialysis system for domestic desalination of brackish groundwater. *In Review*.
- [16] Natasha C. Wright and Amos G. Winter V. Optimal configuration and operation strategies for village-scale electro-dialysis desalination systems. *In Preparation*.
- [17] Sahil R. Shah, Natasha C. Wright, Patrick Nepsky, and Amos G. Winter V. Optimal design of a batch electro-dialysis system for domestic desalination (best paper and presentation award, state-of-the-art category). In *Proceedings of the 2017 IDA World Congress*, 2017.
- [18] Natasha C. Wright and Amos G. Winter V. Model and experimental validation of a spiral-wound electro-dialysis module. In *Proceedings of the 2017 IDA World Congress*, 2017.