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Can Nanoscience Quench a Thirsty World?

By harnessing the power of nanomaterials, three innovators have developed ways to harvest water from the air and make seawater fit to drink.

CALIFORNIA'S RECORD-BREAKING DROUGHT may have ended, but for much of the world, shortages of fresh water are the new norm. Within 30 years, at least one out of every four people on Earth will live in countries with "chronic or recurrent" lack of clean water, according to the United Nations.

New ways to make and purify drinking water

How nanoscience is transforming water tech

Getting rid of lead and other pollutants

Career paths toward water research

The future of these new technologies

Two new devices, with powerful nanotechnologies at their core, offer a way to provide safe, plentiful and affordable drinking water where it is scarcest. One pulls liters of pure water [1] daily from desert air, and the other turns seawater into freshwater [2] in a way that's never been done before. Remarkably, both devices run on only sunlight, making them deployable in nations where electrical grids are limited and fresh water is in short supply.

This roundtable features three of the nanoscientists behind these remarkable technologies. They will discuss their inventions, the science behind them, their potential uses, and the role that nanoscience could play in addressing the global water crisis.

The participants were:

- **MENACHEM (MENY) ELIMELECH** – is professor of chemical and electrical engineering [3] and founder of Yale University's environmental engineering program. He leads a research program to develop long-lasting water purification and desalination membranes at NEWT, the Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment [4].
- **NAOMI HALAS** – is director of the Smalley-Curl Institute [5] and professor of electrical and computer engineering [6] at Rice University and the leader of low-energy desalination research at NEWT. She is a world leader in the study of how nanoparticles transform light into heat.
- **OMAR YAGHI** – is professor of chemistry [7] and co-director of the Kavli Energy NanoSciences Institute [8] at the University of California, Berkeley, and one of the world's most highly cited chemists. He developed the nanomaterials that make it possible to capture water from desert air.

The following is an edited transcript of their roundtable discussion. The participants have been provided the opportunity to amend or edit their remarks. (Image credit (homepage): Asia Development Bank via Flickr, CC-BY-NC-ND 2.0)

Naomi Halas is a professor of electrical and computer engineering at Rice University and a leader in how nanoparticles transform light into heat.(Credit: Jeff Fitlow/Rice University)

THE KAVLI FOUNDATION: ***Water shortages affect billions of people around the world. Is that what drew each of you to this research: to determine how nanotechnology can alleviate a global crisis?***

NAOMI HALAS: That is precisely what draws us to this type of research. These technologies could absolutely make a difference.

MENY ELIMELECH: Yes, we need both adequate water supplies and safe and clean water. These two technologies solve both needs. We can take water from the air, and the same membrane that purifies seawater can also purify brackish or polluted water.

OMAR YAGHI: I agree. Society has always solved serious health and environmental problems with new materials. We're now applying new materials in very clever ways to create a solution that never existed before. So, yes, I am very optimistic that we can make a contribution.

TKF: ***So let's learn more about these promising technologies. Professors Halas and Elimelech, your new technology turns seawater into fresh water. How does your approach differ from conventional desalination used in plants in places like California or the Middle East?***

ELIMELECH: Industrial-scale desalination began after World War II. The first wave of desalination technologies used distillation to evaporate saltwater and condense the steam into drinking water, but this is very energy-intensive because you have to boil water. And while a second process called reverse osmosis does use a membrane to separate pure and salty water more efficiently, it also takes a lot of energy. But now Naomi has developed a new technology that may solve this problem.

HALAS: We have developed nanoparticles that absorb sunlight and convert it into heat. The effect is so powerful that you can put these nanoparticles into ice water and produce steam without using electricity. And because it works with cold water and uses nothing more than sunlight, it eliminates the high energy cost of conventional desalination. In other words, you can do it off the grid, using only a small solar panel to run a pump to deliver water.

> *"Dirty water comes in so many forms. What's exciting is that we can use nanotechnology to develop treatments or chemical sensors for each specific problem."—Naomi Halas*

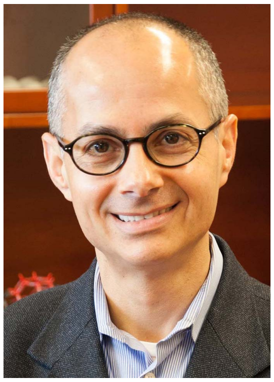
TKF: ***How do your nanoparticles generate such intense heat?***

HALAS: Anyone who has ever burned a hole in paper with a magnifying glass knows that the smaller the spot of light, the hotter it gets. Nanoparticles can capture and focus light on a far smaller spot than any lens. This translates into intense heat in a very small area. No other process can do anything like this.

In this case, we took advantage of the nanoparticle's behavior to create a new type of membrane distillation process. We start with a membrane that blocks liquid water while letting water vapor pass through. Then we attach these nanoparticles to the membrane's surface. When we add seawater and light, the nanoparticles boil the water around them and the steam passes through the membrane, where it condenses back into liquid water without the salt.

TKF: ***Professor Yaghi, we think of desert air as incredibly dry, but there are quadrillions of liters of water in the atmosphere and you've found a way to tap them. Has that been done before?***

YAGHI: No, though many have tried. They've used large sails to condense fog, but this works only where humidity is very high. In arid areas, where humidity is as low as 5 or 10 percent, we cannot do that. Now, thanks to a new type of nanomaterial we have been developing in my lab for the past 25 years, we can trap that water without using electricity.



Omar Yaghi is co-director of the Kavli Energy NanoSciences Institute at UC Berkeley and Berkeley Lab, and one of the most highly cited chemists in the world. (Credit: Berkeley Lab)

TKF: How do nanomaterials make this possible?

YAGHI: I work with metal-organic frameworks [9]—MOFs for short—which are highly porous materials. They are fundamentally different from other porous materials that absorb water from the air. Most other materials bind water tightly, and it takes lots of energy to break those bonds and release the water.

In contrast, we can control the chemistry of MOFs so they bind weakly to water. We can also design cavities that position water so that it forms solid structures that resemble ice.

TKF: ***So you end up with solid water in hot weather?***

YAGHI: Yes, the molecules link to each other in exactly the same way as water in ice. The bonds formed by the solid water attract other water molecules, which helps concentrate the liquid inside the pores, especially in low-humidity environments. To get the water out—our goal is liquid water, after all—we simply expose the material to sunlight. This provides enough energy to break those weak bonds and release it.

TKF: ***So you don't need sunlight to collect water, only to release it?***

YAGHI: That's right.

TKF: ***If I might ask you all, are your inventions part of a larger trend to use nanoscience to transform water technology?***

ELIMELECH: Yes. Water is a latecomer, but we think there are many ways to apply nanoscience to water. Naomi and I are part of NEWT, a multi-university engineering center. Its goal is to transform water treatment via nanotechnology.

HALAS: Dirty water comes in so many forms. What's exciting is that we can use nanotechnology to develop treatments or chemical sensors for each specific problem.

YAGHI: I think this discussion underscores how our understanding of the ways we can use nanoscience is changing. When I was a student, it was all about size. Then we started to discover all the new properties that materials acquired because of their size. With MOFs, we go one step further. These molecules resemble Tinkertoys, with metal hubs and carbon-based rods. By changing the composition and location of the pieces, we can tailor the material chemically and structurally for a particular application.

Incidentally, Naomi, I wanted to ask you about the composition of your nanoparticles. What are they made of?

HALAS: They can be made from many different conductive materials, but for this, we use carbon black, a commercially available carbon nanoparticle used in tires and rubber. Carbon black is a good choice because it is readily available and inexpensive.

Meny Elimelech is a professor of chemical and electrical engineering at Yale University and a world expert in water sustainability.

ELIMELECH: Yet moving forward, we are going to need new materials, because there are so many different types of dirty water and compounds we must remove. This is very difficult with current technologies, so we will need the properties and functionality that nanomaterials provide.

YAGHI: I agree. There is a host of new contaminants in the water supply, coming from pharmaceuticals and personal products. Nanomaterials could help trap these large organic molecules.

HALAS: We also could use sunlight to energize nanomaterials to decompose these larger molecules into smaller and safer ones. I think there are certainly opportunities in both of those directions.

TKF: ***Those are interesting ideas. Professor Halas, could your invention be used to purify polluted water?***

HALAS: We think so. Our process produces very pure water. There are many types of dirty water, and we are investigating different types of contaminants to see what we can reduce.

TKF: ***Do you think it could remove lead from the water in Flint, Michigan?***

HALAS: Yes.

ELIMELECH: In principle, our membrane distillation technology will remove anything that does not turn into a vapor when heated.

TKF: ***So you can remove lead, but not, say, dry cleaning fluid or gasoline?***

ELIMELECH: That's right.

YAGHI: Though we might be able to use Naomi's light-activated nanomaterials to break those volatile pollutants into safer chemicals more effectively than with conventional technologies.

> *"I was born and raised in Amman, Jordan, and the region is very dry. When I was growing up, my family got water from the city once a week, or even once every two weeks."—Omar Yaghi*

TKF: ***I'm curious. Professor Halas and you were working with nanomaterials long before you began to apply them to water. How did you get involved with water?***

HALAS: We were developing a treatment for prostate cancer, which is now in clinical trials at several hospitals. Our idea was to inject nanoparticles so they accumulated around a tumor and shine infrared light on them. That caused the particles to heat up and kill any nearby cancer cells.

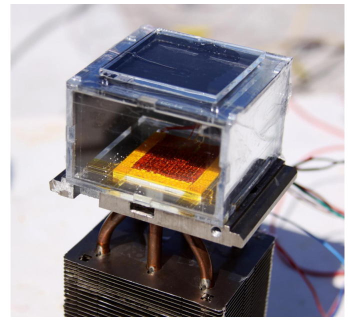
Whenever I discussed the technology, someone in the back of the room would always ask, "Can you use this for solar energy?" I never had a good answer, so we started to investigate the idea. Eventually, we discovered we could vaporize water near those particles, and we tried to understand the physics behind it.

Once we showed we could make steam, the Bill and Melinda Gates Foundation funded us to develop the technology to remediate human waste with steam. We had several other projects going on as well, but it was really the water people, like Meny and Qilin Li at Rice, who got us thinking about how we could combine nanoparticles, membranes and distillation.

ELIMELECH: My background is in water, including membrane desalination and membrane distillation. As part of our collaborative work at NEWT, we helped model how to use her nanomaterials in larger systems. It was a very natural fit.

HALAS: Meny helped us go beyond, "Hey, let's build it and see if it works." If we really want to realize this technology's potential, we need to combine our understanding of nanoparticle physics with an understanding of heat and fluids in membranes, and Meny is really the world's expert in that area.

TKF: ***What about you, Omar?***



This is the water harvester built at MIT with MOFs from UC Berkeley. Using only sunlight, the harvester can pull liters of water from low-humidity air over a 12-hour period. (Credit: MIT photo from laboratory of Evelyn Wong)

YAGHI: I fell into water research because we wanted to remove carbon dioxide from power plant gases, which contain water vapor. We can do this with chemical solutions, but it takes an enormous amount of energy. We thought MOFs would use less energy. But when we tested them, we found that water was competing with carbon dioxide to bind to the molecular framework.

To fix the problem, we needed to measure and understand water uptake. And we discovered that these frameworks bound with water very efficiently, even at low humidity. We could trap water at 77 degrees Fahrenheit (°F) and release it by heating to 113 °F. It turns out that the humidity and temperatures are similar to the average night and daytime temperatures in Tabuk, Saudi Arabia, just south of where I grew up.

Imagine what this meant to somebody like me. I was born and raised in Amman, Jordan, and the region is very dry. When I was growing up, my family got water from the city once a week, or even once every two weeks. Sometimes, I had to wake up at dawn and wait for the water to run, so we could store it in a tank and use it the rest of the time. That leaves an imprint on a child. It’s very satisfying to find a way to use these molecules to provide water.

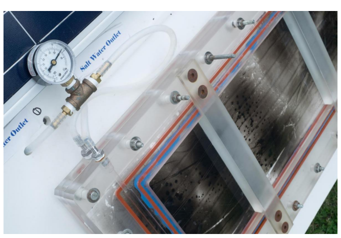
TKF: ***Meny, you also grew up in a desert, didn't you?***

ELIMELECH: Yes, I grew up in Beersheba, a city in Israel's Negev Desert. It was dry, though we had water almost every day. Originally, I wanted to be a farmer working on a kibbutz. But when I started studying water and soil, I liked research so much, I went on to graduate school.

TKF: ***You all have such interesting stories, and often those stories get lost in scientific papers, which make the answers sound so inevitable. Was it really that easy?***

HALAS: You have a point. It is always, "They made it," and "It was done," and they leave out the tear-your-hair-out part. If you are doing something really unusual, you face all sorts of pressures.

Our first solar steam paper was rejected. Two reviewers said it was fabulous, but the third reviewer said it was impossible! But we had vetted our observations for years. We knew we could hold our hand over an iced solution of nanoparticles while it was being illuminated and get second-degree burns.



NEWT's direct solar desalination technology uses carbon black nanoparticles that convert as much as 80 percent of sunlight energy into heat. An earlier prototype could produce as much as six liters of freshwater per hour per square meter of solar membrane. (Credit: Jeff Fitlow/Rice University)

TKF: ***Many scientists, including several winners of the Kavli Prize for Nanoscience [10], have had exactly the same experience.***

HALAS: You develop a thick skin. If you want to work on problems that make a difference, people will challenge you, and that's a good thing. That rejection forced us to go back to the lab for more than a year to understand how this process actually works. It helped us eventually to publish our work with a far deeper understanding of how the effect works, and also to apply our research in other contexts, like water purification.

YAGHI: I’ve had similar experiences. Since we discovered metal-organic frameworks 25 years ago, we have improved them in many different ways. At every step, I faced a barrage of questions from doubters. They were forceful and critical, raising their voices as if I was disputing the foundations of chemistry. It never ends if you break away from the conventional way of doing things. Yet there are also others who study and understand the details and believe in what you are doing. They can be very supportive.

As Naomi said, whenever somebody says, "This is not going to work," it is a challenge for you to show that it does work. So when a student or a colleague comes in and says, "Professor, this didn't work," I answer, "No, you didn't make it work."

Why? Because nature is so rich and has so many surprises, we need to keep working and give it the opportunity to reveal itself to us. In my mind, everything works. When it does not, it is because somebody is not making it work—that's how we solve problems in my lab.

TKF: ***Your new inventions may work off the grid, but they embody very advanced technology. Do you expect that people in developing nations will use them?***

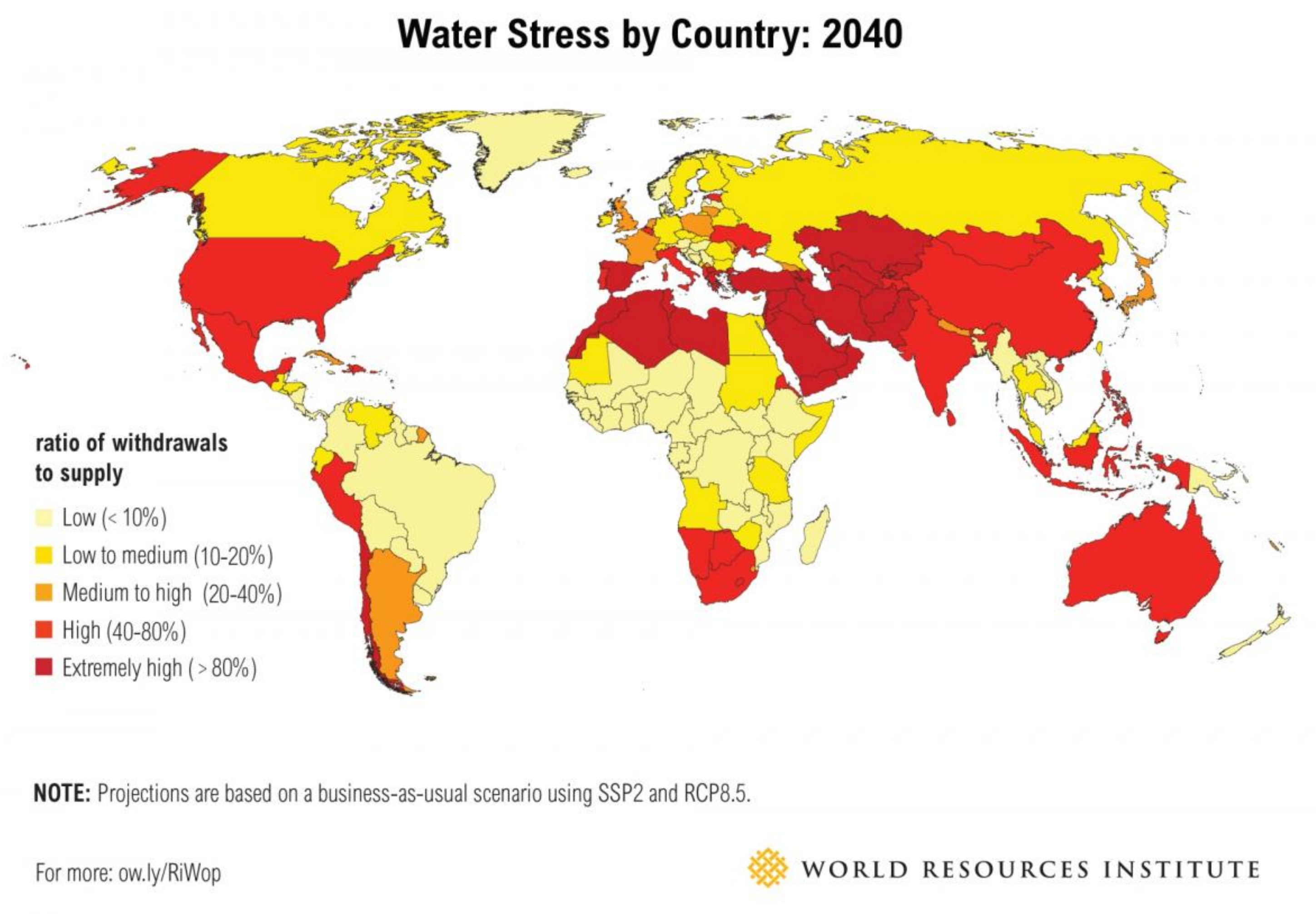
ELIMELECH: We don't need to build low-tech products for developing nations. Even in rural Africa, everyone has cell phones, so why can't they use other advanced technologies? Yet we do not want to build something that they will not be able to operate sustainably. So maybe we need to educate them on how to use it, or combine nanotechnology and automation so that we can control a village membrane system over the Internet. So, yes, it can work.

TKF: ***So, how do you move this technology forward? What comes next?***

ELIMELECH: Scaling up to a commercial product is often difficult, but the capacity of these two processes depends on the area of the membrane alone. The more membrane or framework molecules you make, the more area and the more capacity you get. Unless Omar or Naomi see other obstacles, we can commercialize these products as long as we find a way to reduce the cost.

HALAS: Cost has always been in the back of our minds. We chose to work with carbon black because it is inexpensive and manufactured in developing countries. As researchers interested in sustainability, we want to look at practical alternatives that make widespread commercialization possible.

YAGHI: Scaling up often involves many challenges. Our work involved designing a natural gas fuel tank for automobiles that use MOFs to store more gas under less pressure. Designing that tank raised many issues, but we can build on that engineering knowledge to deploy the best water harvester we can make.



[11]*(Click to enlarge) Map of the world's most water-stressed countries in 2040 (Source: World Resources Institute)*

"We don't need to build low-tech products for developing nations. Even in rural Africa, everyone has cell phones, so why can't they use other advanced technologies?"—Meny Elimelech

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TKF: ***The final question. Scientists often tackle one problem, find a solution, and move onto the next thing. But as this discussion has made clear, meeting the demand for fresh water is more than an intellectual exercise. Your research really can change the world. Has this changed how you think about your work?***

HALAS: My thesis advisor once said that one should ideally envision a 15-year research career, long enough for some continuity but finite. What he meant was, are you going to spend those years dotting the I's and crossing the T's of other people's breakthroughs, or are you going to do something original of your own? I wanted to do something original and important, like applying nanophotonics to water and cancer.

ELIMELECH: I started out doing more fundamental research without thinking about the applications, but over the past 10 or 15 years, I have been working more on solving problems that are important to people. If I can help solve global water scarcity, it would be great.

YAGHI: When I started my career, I was interested in solving intellectual problems. That was chemistry. Applications were engineering, and somebody else's problem. This helped me focus on learning to synthesize MOFs that had the properties I wanted.

This work brought me into contact with CEOs, and one day, one of them asked, "What are these molecules good for?" And I thought, "What kind of question is that? I am an intellect, almost like an artist."

And he said, "Omar, you can be an excellent scientist and win all the science awards, but you're never going to be a great scientist unless you show how your work is important to society."

These water applications have a chance to impact society and help solve real problems facing people around the world. This really came home to me when I receive an email from somebody who wanted to use these nanomaterials for agriculture. They were not ready for deployment, so I delayed a response. And he wrote again, saying, "It is not your right to keep this technology from us. It is humanity's right to use this technology."

It was eye-opening because it is humanity's right to use this technology. When I am in my lab, I try to keep his email in mind and think about the impact we could on real people around the world.

—Alan Brown, Fall 2017

Science Tags:
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