Communicating Research to the General Public

At the March 5, 2010 UW-Madison Chemistry Department Colloquium, Prof. Bassam Z. Shakhashiri, the director of the Wisconsin Initiative for Science Literacy (WISL), encouraged all UW-Madison chemistry Ph.D. candidates to include a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

Over 50 Ph.D. degree recipients have successfully completed their theses and included such a chapter.

WISL encourages the inclusion of such chapters in all Ph.D. theses everywhere through the cooperation of Ph.D. candidates and their mentors. WISL is now offering additional awards of $250 for UW-Madison chemistry Ph.D. candidates.

Wisconsin Initiative for
Science Literacy

The dual mission of the Wisconsin Initiative for Science Literacy is to promote literacy in science, mathematics and technology among the general public and to attract future generations to careers in research, teaching and public service.

UW-Madison Department of Chemistry
1101 University Avenue
Madison, WI 53706-1396
Contact: Prof. Bassam Z. Shakhashiri
bassam@chem.wisc.edu
www.scifun.org

Development of Electrode Materials for Electrochemical Desalination and Solar Water Splitting

By

Margaret A. Lumley

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Chemistry)

At the

UNIVERSITY OF WISCONSIN-MADISON

2020

Date of final oral examination: June 18th, 2020

This dissertation is approved by the following members of the Final Oral Committee:

Kyoung-Shin Choi, Professor, Chemistry

Randall Goldsmith, Professor, Chemistry

Song Jin, Professor, Chemistry

Robert Hamers, Professor, Chemistry

Chapter 2

Removing Salt from Seawater with a Desalination Battery: An Introduction for the General Public

This chapter was written in fulfillment of the requirements for Wisconsin Initiative for Science Literacy Graduate Thesis Award for Communicating Research to the Public

2.1 CONTEXT

Throughout my time in graduate school, I have dedicated myself to performing research that has the potential to benefit people across the world. The scientific research that I am doing belongs to all of us and so it is only right that I should be able to communicate that science in a way that is accessible to a broad audience. While I have practiced communicating my research to my family and friends with non-scientific backgrounds for many years, my first formal experience with this endeavor came in 2018 when I participated in the Three Minute Thesis competition at UW-Madison (co-sponsored by the Wisconsin Initiative for Science Literacy). The Three Minute Thesis competition is exactly what it sounds like; you have just three minutes and one slide to explain your thesis research to a general audience. The presentations are judged by a panel of experts in communication and my presentation was awarded third place in 2018. About a year later, I was invited to give a seven-minute pitch at the annual Wisconsin Alumni Research Foundation (WARF) Innovation Day. WARF Innovation Day is an event designed to showcase innovative research being done on the UW-Madison campus. This event was open to the general public and the audience consisted of other researchers, government officials, venture capital firms and investors, and industry experts, to name a few examples. I was fortunate to receive input from WARF to help me craft a pitch that was engaging and easy for a general audience to understand. I have written this thesis chapter as a part of my responsibility as a scientist to embrace scientific communication and make the complex scientific research that we do in academic more accessible. I would like to thank the Wisconsin Initiative for Science Literacy at UW-Madison for providing this platform, and for sponsoring and supporting the creation of this chapter.

2.2 INTRODUCTION

Desalination is defined as the process of removing salt from *saline*, or salty water. The most abundant source of saline water on Earth is seawater, and you may have heard of desalination as a strategy that can be used to convert seawater into fresh, drinkable water. While this concept seems straightforward, desalination of seawater is actually very challenging, and the most advanced desalination technologies available today still have significant limitations. During my doctoral research, I have worked to develop a new desalination technology that can overcome some of the conventional limitations of seawater desalination. The technique that I use to perform desalination is *electrochemistry*; the branch of chemistry that combines electricity and chemical reactions. To understand my research, it is first important to understand why desalination is important and the drawbacks of existing desalination methods. In the sections that follow, I will break down each element of this chapter titled: "*Removing Salt from Seawater with a Desalination Battery,*" and explain how these different concepts can work together to enable more efficient desalination. My hope is that when you finish reading this chapter you will know a little bit more about desalination and electrochemistry and how electrochemistry can be used to construct a *desalination battery*.

2.3 HOW MUCH WATER DO WE ACTUALLY USE?

In Madison, WI, we are pretty lucky when it comes to access to freshwater; most of us don't wake up worried that our sinks won't turn on. In fact, if your morning routine is anything like mine, it is centered around water. You wake up, take a drink of water, flush your toilet after using the bathroom, turn on the faucet to wash your hands, turn on the showerhead to take a shower, make breakfast and wash your dishes, turn on the faucet to brush your teeth, and fill up your water bottle before you leave the house. In the United States, the average person uses about

100 gallons of water per day for regular household activities such as showering, doing laundry, and washing dishes. With 100 gallons of water you could fill up about half of a hot tub, two and a half bathtubs, or about six and a half beer kegs! The average American uses ~37,000 gallons of household water per year; more than enough to fill a large backyard pool. However, household water represents only a small fraction of the total water that humans actually consume in a year.

Agriculture accounts for about 70% of global freshwater usage. For example, it takes 34 gallons to produce one 5-ounce serving of wine, 240 gallons to produce a loaf of bread, 380 gallons to produce a pound of cheese, 520 gallons to produce a pound of chicken, and 1,800 gallons to produce a pound of beef. The average American consumes 270 pounds of meat per year. To produce that amount in chicken would require 140,400 gallons of water per year and to produce that amount in beef would require 486,000 gallons of water per year, just to make enough meat for one person. Water is used in virtually every aspect of our lives; it is required for the power plants that produce electricity, to make the clothes that we wear, to produce gasoline that we use to drive our cars, and to make the cars themselves. There is no simple way to quantify the amount of water that we consume because a lot of the water that we use is hidden in these other processes. Nevertheless, these examples put into perspective the importance of access to freshwater.

2.4 DESALINATION AS A STRATEGY TO ADDRESS FRESHWATER SCARCITY

Steady growth in human population and rapid industrial development have led to greater demands for water production for agriculture, energy generation, and human consumption, and lack of access to freshwater is becoming an increasingly critical issue. Water scarcity is defined broadly as a lack of sufficient freshwater resources to meet water demands and is classified in terms of the amount of freshwater available per person per year. Periodic or limited water shortages can be expected when water supplies are between 264,000 gallons (1,000 cubic meters) and

448,800 gallons (1,700 cubic meters) per person per year. **Figure 2.1** illustrates that water scarcity is a challenge across the globe; 4 billion people (66% of the world's population) live without sufficient access to freshwater for at least one month of the year and 500 million people face water scarcity all year round.[1] The world's most water stressed region is the Middle East. In the United States, water scarcity is a challenge primarily in southern states, such as Texas and Florida, and western states, such as California.

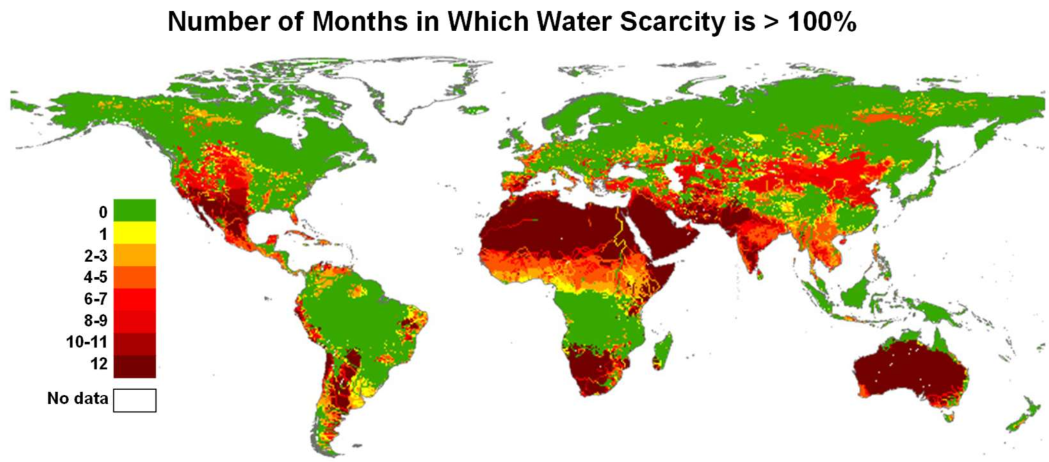

Figure 2.1. A map showing parts of the world that suffer from water scarcity. The dark red regions highlight parts of the world where the population suffers from water scarcity all year round.[1]

I was born and raised in California and lived there until I moved to Madison in 2015. California experienced its longest drought from December 2011 to March 2019, lasting for a total of 376 weeks. From 2014 to 2017 California was in a period of "exceptional drought," which is defined as widespread crop/pasture loss and severe water shortages that cause water emergencies. During this time, water was so scarce that the governor imposed a mandatory statewide 25% reduction in water use. As California is a major producer of crops such as almonds, broccoli, and tomatoes, this lack of water directly impacted the entire nation. Thus, while many people may think of water scarcity as a challenge only in countries with arid climates far from the United States, it actually has the potential to affect our daily lives in profound ways.

These statistics may be surprising when we consider that about 70% of the Earth's surface is covered in water (**Figure 2.2**). However, taking a closer look at the composition of that water reveals that almost 97% of the water on Earth is seawater that we can't drink because of its high salt concentration. In fact, only 2.5% of the water on Earth is freshwater and only 1% is available for human consumption; the remaining freshwater is frozen in polar ice caps. Because of the vast abundance of seawater on Earth, removing salt from seawater (*desalination*) is considered the most viable option to meet the increasing global demand for freshwater.

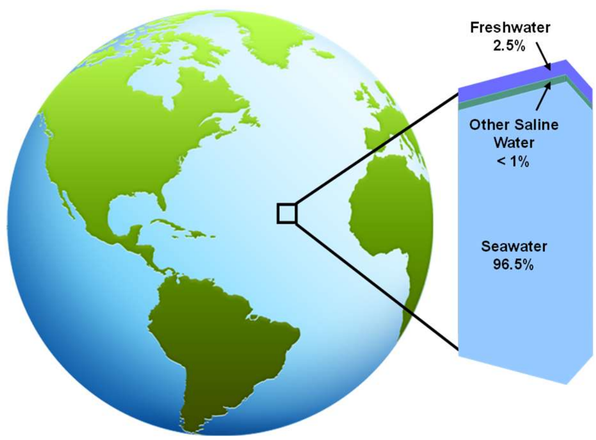

Figure 2.2. The distribution and composition of Earth's water.

The primary methods currently used for seawater desalination are *thermal distillation* and *reverse osmosis* (RO), with ~35% and ~60% of desalinated water produced globally coming from distillation and RO, respectively.[2] *Thermal distillation* relies on heat energy to boil seawater followed by re-condensation to generate freshwater and leave the salt behind (**Figure 2.3a**). If you have ever gone swimming in the ocean, you might have experienced the feeling of salty residue on your skin after you dry off in the sun. After you take a dip in the ocean, your skin is covered in salt water. When you dry off in the sun, the water will evaporate while the salt is left behind. Although distillation seems quite simple, it is actually extremely energy intensive and is suitable primarily in areas that contain an abundance of cheap fuel. One strategy that has been adopted to reduce the amount of energy used for distillation is integrating distillation plants with other systems that generate excess heat, like power plants, so that the excess heat can be repurposed and used for distillation. However, this approach is not suitable in all geographic locations, and the construction of new distillation plants has slowed in recent years.[2]

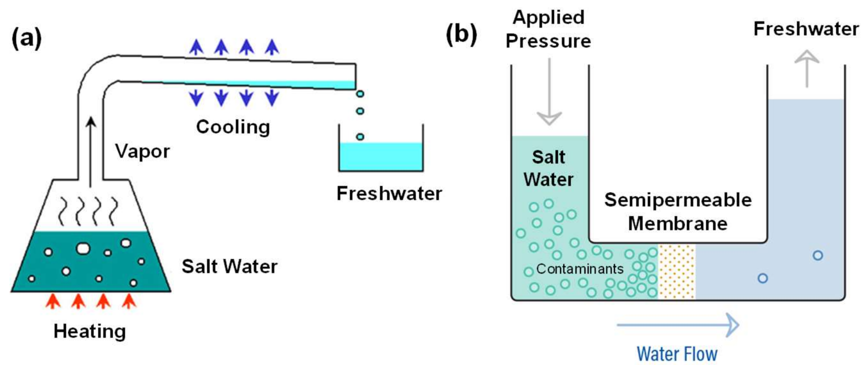

Figure 2.3. Schematic of (a) thermal distillation[3] and (b) reverse osmosis.[4]

Reverse osmosis (RO) is the most energy-efficient technology currently available for seawater desalination, although it still has some drawbacks. RO relies on the use of a *semipermeable membrane*, which is a membrane that allows some substances to pass through but not others. In RO, the semipermeable membrane allows water to pass through but rejects salt. A high-pressure pump is required to force water through the membrane (**Figure 2.3b**). On one side of the membrane, freshwater is produced and on the other side of the membrane water with a high salt concentration, called *brine*, is left behind. Brine is something you may be familiar with if you have ever "brined a turkey" on Thanksgiving by soaking it in really salty water. One major challenge of RO is that particles accumulate on the membrane, causing its performance to degrade over time. To mitigate this particle accumulation, pre-treatment of water is required, which involves filtration, sterilization, and the addition of chemicals. Even after these pre-treatment steps, regular membrane maintenance is still necessary, increasing the cost of desalination. In addition, the need for high-pressure pumps means that RO still requires a significant amount of energy.

As the demand for freshwater continues to grow, desalination is becoming an increasingly attractive and important strategy for freshwater production. This is reflected in the increase in the global water desalination market value; in 2017, the global water desalination market value was estimated to be $16.4 billion and is expected to increase to $37.6 billion by 2026.[5] The global desalination capacity is also predicted to double from 2015 to 2030 (**Figure 2.4**).[6] Thus, the discovery of new, energy-efficient desalination methods that can address the limitations of conventional technologies are primed to have a dramatic impact on global freshwater production.

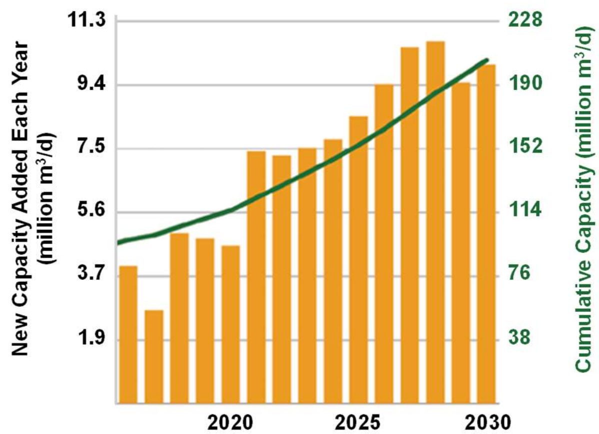

Figure 2.4. Projected increase in global desalination capacity up to the year 2030.[6]

2.5 ELECTROCHEMISTRY: COMBINING ELECTRICITY AND CHEMISTRY

In my research group, we use a technique called *electrochemistry*. Electrochemistry is the branch of chemistry that involves the relationship between electricity and chemical reactions; electricity can be used to drive a chemical reaction, or a chemical reaction can be used to produce electricity. Even though we may not think about it, electrochemistry is used to make many of the products we use every day. For example, *electroplating* is a process that uses electrochemistry to apply a metal coating onto an object. Gold-plated jewelry is made by electroplating a thin layer of gold onto a piece of jewelry made from a cheaper metal, like copper.

There are many different types of electrochemical reactions, but they all involve the flow of *electrons* (e^-), or negatively charged particles. For an electrochemical reaction to occur, one species must lose electrons, called *oxidation*, and one species must gain electrons, called *reduction*. The flow of electrons is what you measure when you measure electricity. To study electrochemical reactions, I use an electrochemical cell (**Figure 2.5**). An electrochemical cell is composed of two materials that can conduct electricity called *electrodes* that are immersed in a solution then can conduct electricity called an *electrolyte*. Metals like copper or silver are examples of conductors that can be used as *electrodes*. *Electrolytes* typically contain dissolved salt and we sometimes consume electrolytes after physical activity in the form of a sports drink like Gatorade. In an electrochemical cell, the two electrodes are connected by a wire that allows electrons to travel from one electrode to the other. The electrode that loses electrons (oxidation) is called the *anode* and the electrode that gains electrons (reduction) is called the *cathode*. A handy mnemonic to remember this relationship is **AN OX** and **RED CAT**: <u>Ox</u>idation at the <u>An</u>ode and <u>Red</u>uction at the <u>Cat</u>hode. The electrochemical cell is also connected to a device that can measure the flow of electrons (current) or can supply external energy, like a battery.

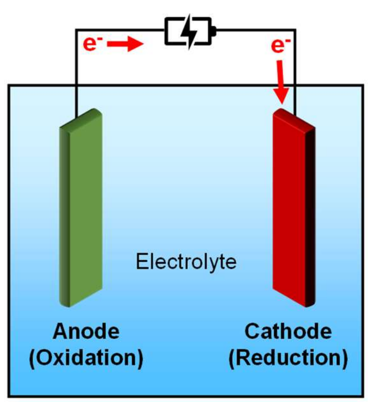

Figure 2.5. Schematic of an electrochemical cell showing electrons flowing from the anode to the cathode. Electrons are represented by the symbol e^-.

One of the most common examples of electrochemical reactions that we encounter every day is a battery. Each one of us carries a battery around with us in our cell phones and there is a battery powering the laptop that I am using to write this chapter. Batteries generate electricity to power our cell phones during the day though *discharging* and must be plugged in at night to *charge*. Discharging is defined as a spontaneous electrochemical reaction that generates an energy output, and charging is defined as a non-spontaneous electrochemical reaction that requires an energy input. A *spontaneous* reaction is one that proceeds without any outside help, which is why our phones don't need to be constantly plugged into a power source. Spontaneous processes also occur in other parts of our lives.

For example, in the past few months, I have taken up biking. While Madison has relatively flat biking terrain, there is a massive hill leading out of Vilas Park referred to as the Edgewood Hill. If you are riding into Vilas Park on your bike, you can coast down the hill without needing to pedal, which is a spontaneous process. However, if you are unlucky and are travelling in the other direction, you will need to pedal your bike to get up Edgewood Hill, which is a non-spontaneous process that requires outside power, supplied by your legs pedaling the bike (**Figure 2.6**). Just like these physical processes, electrochemical reactions can also occur spontaneously and generate energy (discharging) or non-spontaneously and require energy (charging). In electrochemistry the spontaneity of a reaction is determined by the difference in the *reduction potentials* of the two electrodes used in the electrochemical cell. The *reduction potential* of a material is a measure of how likely (or unlikely) it is to gain electrons and is reported in terms of volts (V).

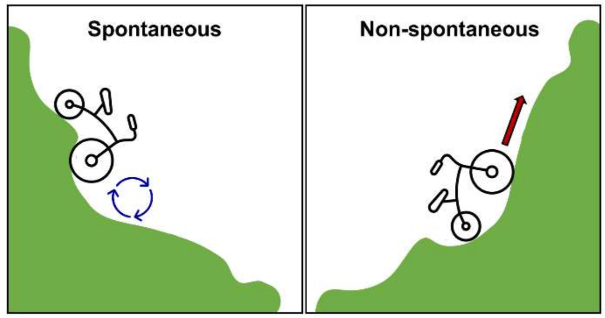

Figure 2.6. An example of spontaneous and non-spontaneous processes. When you bike down a steep hill you can simply coast without pedaling (spontaneous). To climb back up the hill you have to provide some energy, which comes from using your legs to pedal the bike (non-spontaneous).

The lithium ion (Li-ion) batteries that we all carry around with us in our cell phones operate using spontaneous and non-spontaneous reactions. Li-ion batteries consist of two electrode materials and an electrolyte, just like the electrochemical cell I described above. The electrolyte contains a dissolved form of lithium that has a positive charge (Li^+). This type of charged species is called an *ion*. The Li^+ ions will be shuttled back and forth between the two electrodes during discharging and charging, like when you throw a ball back and forth when you play catch. During discharging, Electrode I will lose electrons and release Li^+ from the structure (**Figure 2.7**). The electrons and Li^+ will move from Electrode I (anode) to Electrode II (cathode) so that Electrode II gains electrons and stores Li^+. In batteries, electrons and ions always move together. In this example, electrons flow *spontaneously* from Electrode I to Electrode II, generating energy, just like riding a bike down a hill. This energy is what we use to power our devices. Once this process is complete and our batteries are dead, they need to be charged so that they can be used again. During charging, electrons and Li^+ must be forced to move in the reverse direction from Electrode II to Electrode I. Electrode II loses electrons and Li^+ (anode) and Electrode I gains electrons and Li^+ (cathode). This process is *non-spontaneous* and requires an energy input that is supplied when we plug our cell phones into a power outlet, just like we have to pedal our bikes up a hill.

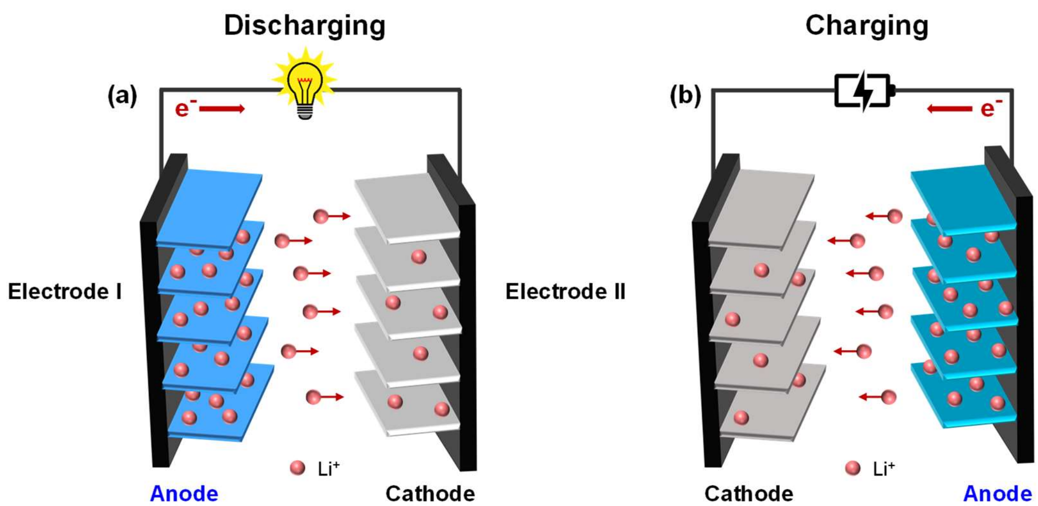

Figure 2.7. Schematic of a Li-ion battery. (a) Discharging: electrons (e^-) and Li^+ flow spontaneously from Electrode I (anode) to Electrode II (cathode), generating energy. (b) Charging: A power supply is used to force electrons (e^-) and Li^+ to flow from Electrode II (anode) to Electrode I (cathode).

2.6 ELECTROCHEMICAL DESALINATION: A DESALINATION BATTERY

The principles that I described above for Li-ion batteries are what I have used during my dissertation work to construct a *desalination battery* that can be used to remove salt from seawater. Salt in seawater is composed of the ions sodium (Na^+) and chloride (Cl^-). Na^+ is a positively charged ion called a *cation* and Cl^- is a negatively charged ion called an *anion*. Salt that we put on our food or that we use to de-ice the roads in the winter also contains Na^+ and Cl^-. To remove salt from seawater, we need to pair a material that can store Na^+ with a material that can store Cl^-. By combining these materials, we can construct a *desalination battery*. Like conventional batteries, the desalination battery stores and releases energy during the charging and discharging processes. However, in the desalination battery, the energy storage and release processes are coupled with the removal and release of Na^+ and Cl^-. A unique feature of batteries is that the energy consumed during charging can be recovered during discharging. This is similar to the process of buying and reselling furniture, for example. When you buy a couch, you have to spend money to make the purchase (charging) but if you resell the couch you can get some of that money back (discharging).

Therefore, the net energy consumption required for desalination with the desalination battery can be drastically reduced compared with thermal distillation and reverse osmosis. A unique feature of our desalination battery is that it actually *generates* energy concurrently with salt removal to achieve simultaneous energy generation and desalination. This is unlike other desalination technologies that *consume* energy during desalination.

In the desalination battery, seawater is used as the electrolyte. When the Na-storage and Cl-storage electrodes are immersed in seawater, the Cl-storage electrode will lose electrons (oxidation) coupled with the insertion of Cl^- and the Na-storage electrode will gain electrons (reduction) coupled with the insertion of Na^+ (**Figure 2.8a**). One way to remember how electrons and ions move together is by thinking about a magnet. Electrons (e^-) and anions, like Cl^-, are both negatively charged and will always move in opposite directions, like how two south poles of a magnet will repel each other. Electrons (e^-) and cations, like Na^+, are oppositely charged and will always move in the same direction. In the system that we study, electrons flow *spontaneously* from the Na-storage electrode to the Cl-storage electrode, which means that the removal of Na^+ and Cl^- from seawater will produce energy. Once the electrodes become saturated with Na^+ and Cl^-, the electrodes will need to be regenerated so that they can be used for subsequent desalination cycles. To regenerate the electrodes, they can be moved to a second solution to release Na^+ and Cl^-. By supplying external energy, electrons are forced to move in the opposite direction (**Figure 2.8b**). The Na-storage electrode will lose electrons (oxidation) coupled with the release of Na^+ and the Cl-storage electrode will gain electrons (reduction) coupled with the release of Cl^-.

One challenge of reverse osmosis is that it produces both freshwater and brine. This is problematic because the brine must be disposed of in some way. The desalination battery also produces brine during the electrode regeneration step. However, to reduce the environmental impact of our technology, we can use wastewater generated by some other process, like battery manufacturing or electric power plants, as the electrolyte used for the electrode regeneration step. In this way, we can increase the salt concentration of already existing wastewater rather than produce a larger volume of new wastewater.

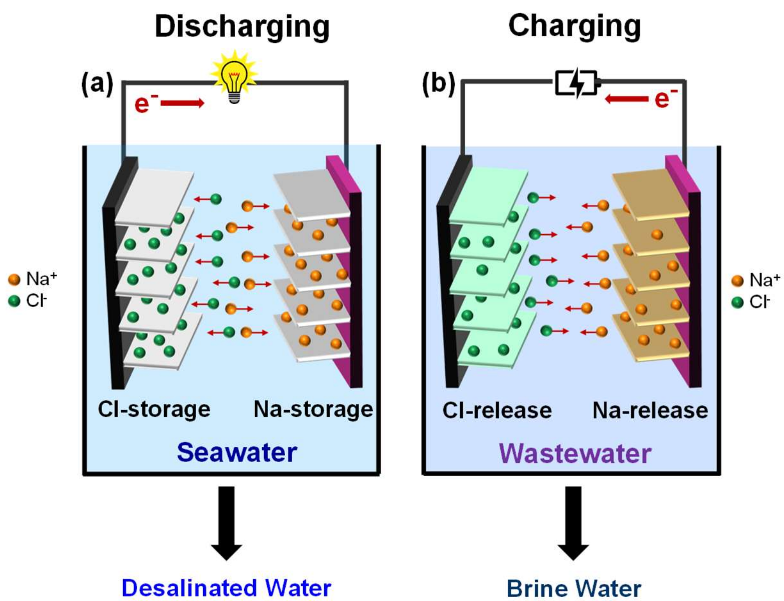

Figure 2.8. Schematic of the desalination battery. (a) During desalination, electrons (e^-) will flow spontaneously from the Cl-storage electrode to the Na-storage electrode, generating an energy output (*discharging*). (b) To regenerate the electrodes, they will be moved to a second solution. By supplying external energy, the electrons (e^-) are forced to flow from the Na-storage electrode to the Cl-storage electrode, releasing Na^+ and Cl^- through charging.

There are two major advantages offered by our desalination battery that are not currently offered by any other technology. The first is that our desalination battery can operate without the use of a membrane because it involves ion-specific electrode reactions. This eliminates all of the costs associated with the prevention of particle accumulation on the membrane required for reverse osmosis and simplifies the overall cell design. The second is that our desalination battery couples salt removal with energy generation: when our electrodes are simply immersed in seawater, they will simultaneously remove salt ions and generate energy. These features make the desalination battery uniquely positioned to address the limitations of existing desalination technologies.

The first desalination battery was reported by another research group in 2012 using silver metal (Ag) as the Cl-storage material. However, silver is too expensive to use for practical, large-scale applications because the cost of the materials used in desalination technologies directly affects the cost of the water produced by desalination. In 2017, a research scientist in my lab, Dr. Do-Hwan Nam, discovered that bismuth metal (Bi) can be used as a Cl-storage material and he patented this discovery. Bi can be oxidized to bismuth oxychloride (BiOCl) to remove Cl^- from seawater. Bismuth is the active ingredient in Pepto-Bismol and bismuth oxychloride is used in cosmetics like eyeshadow and nail polish to make them shimmer. In 2019, the cost of silver was $570 per kilogram and the cost of bismuth was $7.50 per kilogram, illustrating that bismuth is clearly a more cost-effective option for industrial-scale desalination batteries.

2.7 MY RESEARCH: INVESTIGATION OF Na-STORAGE ELECTRODES

My doctoral research has focused specifically on the development of Na-storage materials. For practical desalination applications, the Na-storage material must be inexpensive and must efficiently store and release Na^+ in seawater with long-term stability. The type of Na-storage material that I have investigated is closely related to Prussian Blue and is called a Prussian Blue Analogue (PBA). Prussian Blue is most well-known for its dark blue color and is commonly used as a pigment in paints. Prussian Blue has a cost of less than $1 per kilogram. PBAs are ideally suited for large-scale desalination applications because they are inexpensive, easy to produce, and have a porous structure that makes it easy for ions, like sodium, to be inserted and released. Other research groups have also studied PBAs for desalination, but all have reported degradation in the performance of their materials over time. This phenomenon also occurs in our cell phone batteries and is the reason that we need to charge our phones more frequently as the battery ages. An important metric to use for the evaluation of electrode materials is how many times they can be used with no loss in performance, or the lifetime of the electrode. If the lifetime of the electrode is short then it will need to be replaced frequently, which is expensive and inconvenient.

During my dissertation research, I have explored a few different types of PBAs and have investigated how the conditions used to make the material, like the temperature at which the material is made, affect its size and shape, referred to as its *morphology*. For example, I have made PBAs that are composed of small spherical nanoparticles (**Figure 2.9a**) and larger cube-shaped particles (**Figure 2.9b**). By optimizing the synthesis conditions for PBAs, I have been able to improve the lifetime of the resulting electrodes from 20 cycles to > 500 cycles. This is equivalent to improving the lifetime of the electrode from 20 days to ~1.5 years if we perform one desalination/electrode regeneration cycle per day. My research group recently summarized our findings in a manuscript that other research groups can use as a guide for how to prepare high-performing and stable PBAs. I am continuing to modify the way that I make these materials to further improve their lifetime.

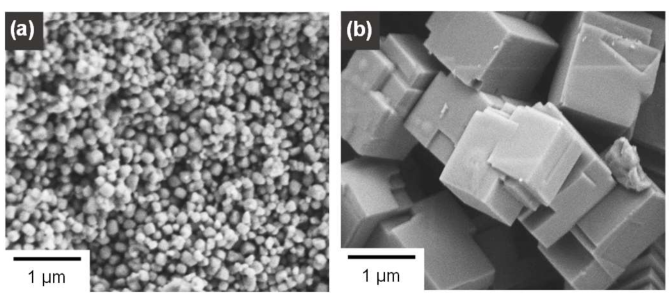

Figure 2.9. Image of Prussian Blue Analogues composed of (a) small spherical particles and (b) larger cube-shaped particles.

To construct a complete desalination cell, we can then combine the bismuth (Bi) electrode and the PBA electrode (**Figure 2.10**). This figure summarizes all of the different concepts that I have discussed so far in this chapter. When the two electrodes are simply immersed in seawater, electrons will flow *spontaneously* from the Bi electrode to the PBA electrode, generating energy (*discharging*). The Bi electrode will remove Cl^- from the electrolyte and the PBA electrode will remove Na^+ from the electrolyte to achieve desalination. When the process is complete, the electrodes can be moved to another solution to perform the electrode regeneration or *salination* step. By providing external energy (*charging*), the electrons are forced to move in the reverse direction from the Bi electrode to the PBA electrode. The Bi electrode will release Cl^- and the PBA electrode will release Na^+. Importantly, the energy that is required for the electrode regeneration step can be recovered during the desalination step, reducing the total amount of energy required for desalination. At this point, we can recover 86% of the energy required for the salination step during the desalination step and we are continuing to improve this number.

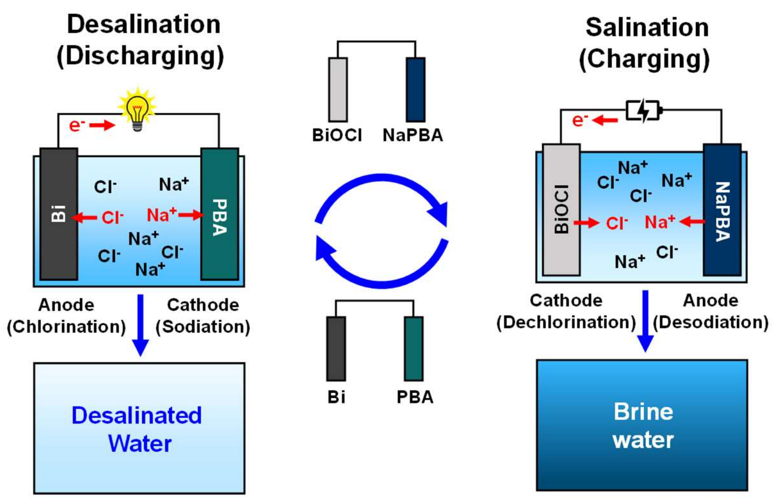

Figure 2.10. Schematic of a desalination battery using Bi and PBA electrodes. During desalination, electrons will flow spontaneously from the Bi electrode to the PBA electrode, generating energy (discharging). During salination, external energy is required for electrons to flow in the opposite direction and regenerate the electrodes (charging).

2.8 CONCLUSION AND NEXT STEPS

In summary, during my doctoral research I have contributed to the development of a desalination battery that can simultaneously remove salt from seawater and generate electricity. Our desalination battery technology addresses the most critical limitations of existing seawater desalination technologies to enable more efficient desalination. I have specifically worked on developing an Na-storage material that is inexpensive and easy to produce. Through careful design of synthesis conditions, I have been able to fabricate an electrode that can operate with no loss in performance for 500 desalination/electrode regeneration cycles, equivalent to a lifetime of ~1.5 years. To date, this is the best stability reported for any Prussian Blue Analogue for desalination applications! By pairing this material with a Cl-storage material that was discovered by another member of my research group, we can now perform desalination and salination with 86% energy recovery.

After I graduate, I will be staying in my research lab as a postdoctoral researcher to build a prototype desalination device. Currently, the electrodes that we use are about the size of a penny and can only be used to remove salt from < 1 mL of water. The next step is to increase the size of our electrodes to build a prototype device that is 10,000 times larger than our current lab scale cell and can remove salt from 1 L of water. Our ultimate goal is to use this technology for real industrial scale desalination. In fact, we are even considering forming a startup! I will be a founder of the startup with Dr. Nam and my research advisor, Prof. Kyoung-Shin Choi. Therefore, in addition to my research, I have also invested a lot of time into my entrepreneurial education and have been actively engaging with community partners that may benefit from our desalination technology.

We have also been exploring other applications of our technology. For example, using bismuth to remove chloride from wastewater treatment plant effluent water is another compelling application of our technology. The widespread use of water softeners leads to the presence of high amounts of chloride in wastewater, which ultimately gets discharged into freshwater streams or rivers and is harmful to aquatic life. These high levels of chloride can also come from food manufacturers who use salt in their food manufacturing process, like pickle plants or soy sauce plants. Salt and chloride regulations are quickly becoming a significant obstacle to growth for food companies in Wisconsin. To explore how our technology could be used to solve some of these challenges, we have formed partnerships with a local wastewater treatment plant, pickle plant, and engineering firm that specializes in wastewater treatment. With support from these partners, we were recently awarded a grant from the Baldwin Wisconsin Idea Endowment. This grant is awarded to projects that foster public engagement and advance the Wisconsin Idea; the notion that the knowledge and solutions generated at UW-Madison will benefit the people of Wisconsin, the nation, and the world. Our research team is committed to technology translation efforts to use our desalination technology for real world water treatment applications. We will continue to increase the size of our desalination device and work with community partners to use our technology to make a positive impact.

2.9 REFERENCES

(1) Mekonnen, M. M.; Hoekstra, A. Y. Four billion people facing severe water scarcity, *Sci. Adv.*, **2016**, *2*, e1500323.

(2) Jones, E.; Qadir, M.; van Vliet, M.T.H.; Smakhtin, V.; Kang, S.-m. The State of Desalination and Brine Production: A Global Outlook. *Sci. Total Environ.* **2018**, *657*, 1343─1356.

(3) *Thermal Technologies*. http://www.roplant.org/contents.asp?Depth1=6&Depth2=1 (Accessed May 5th, 2020).

(4) *What is Reverse Osmosis?* https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis (Accessed May 5th, 2020).

(5) *Water Desalination Market By Technology- Growth, Future Prospects & Competitive Analysis*; 59294-09-18; Credence Research; San Jose, CA, 2018.

(6) International Desalination Association News: Focused on Desalination and Water Reuse, 2015. https://idadesal.org/wp-content/uploads/2018/11/idanews_151112.pdf (accessed November 6th, 2019).

(7) *What is Electroplating?* https://www.srcplating.com/what-is-electroplating-stricker-refinishing-src-plating-cleveland-ohio/ (Accessed May 5th, 2020)