Simple, sustainable, water straight from the sun - batteryless electrodialysis desalination

by

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Abstract

There is a need for reliable, low maintenance off-grid desalination for drinking water in resource-constrained regions. However, current off-grid desalination systems rely on large solar arrays and battery capacity for sufficient power and energy storage - such systems greatly increase the capital costs, operating costs, complexity and maintenance. Electrodialysis is a flexible technology with significant energy and water efficiency in comparison to other thermal and membrane processes and thus provides significant reduction in solar array capacity; however, it has not been exhibited off-grid without significant energy storage. This work proposes and validates a simple, robust, and maximal water production rate control scheme which enables batteryless off-grid desalination. The control scheme proposed involves cascade control with an outer PID loop tracking power and commanding flow rate, and a coupled inner model based control loop which always produces the maximum allowable current and thus, maximum desalination rate for the real-time power. This control scheme is applicable and adaptable to any continuous power system but can be most advantageous in direct-drive variable power situations, such as with solar panels. The controller is extremely simple, computationally efficient, and robust to implement: it relies on two sensors - a flow meter and a conductivity meter, one equation, and a PID controller. We demonstrate and conduct initial validation of this capability in a field pilot using direct-drive photovoltaic batch electrodialysis. We demonstrate a battery reduction of 99.4% from comparable prior art (20 kwh to 120 wh) on a 2 kwh system at a control speed of 100 milliseconds and utilization of 79% and 91% of total solar energy on two separate days of testing. This control scheme enables significant reduction and even elimination of batteries and is a step towards minimal-maintenance, high production off-grid desalination.

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"Imagination will often carry us to worlds that never were. But without it, we go nowhere." - Carl Sagan

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Chapter 1

Introduction

1.1 The need for robust desalination in global development and humanitarian crises

Desalination is a growing problem for water treatment and is increasingly occurring in areas historically prone to natural disasters and conflict. There consequently is an increasing need for simple, robust, low-maintenance, off-grid saline water treatment in humanitarian scenarios and in resource-constrained, developing regions.

Humanitarian crises ranging from acute natural disasters to long-term refugee or internally displaced persons (IDP) encampments are becoming more prevalent with global climate developments [1]. In parallel, there are many regions around the world that are experiencing water shortages and water salinization. These regions often overlap, and thus, there is a need for desalination in crises and generally in developing regions of the world (Fig. 2-4). Humanitarian response currently has no standard and well-accepted practices for treating chemicals, including salinity in emergencies [2–10]. This is true at all time scales, from acute emergencies like coastal flooding to protracted scenarios such as saline boreholes in refugee camps. Currently, there is no standard deployable desalination system that meets the requirements of humanitarian relief.

Military scenarios and some humanitarian cases have historically used diesel powered reverse osmosis systems to purify and desalinate sea and brackish water [11–13]. In recent times, armies have heavily relied on shipping bottled water [14]. Relatively high-income countries have a more robust supply chain and can rely on this shipped water, however, shipping alone is not as viable for disasters and conflict in economically developing countries with little to no infrastructure. Population dense, relatively static acute and protracted emergencies are well suited for bulk water treatment (BWT) schemes; a robust, deployable desalination system fits into this segment of interventions.

Unfortunately, there is a lack of robust, deployable desalination systems for humanitarian crises and off-grid systems in the developing world. This is mainly attributed to the highly constrained environment which limits the use of consumables, requires rapid deployment speed in the case of acute emergencies, and necessitates simplification of operation and maintenance. Such requirements are often secondary thoughts, are difficult to quantify, and differ from stable, commercial situations where operations are supported by accessible supply chains as well as a network of operators and technicians. Batteries in particular are a major pain point due to shipping regulations, maintenance, and operational complexity [15].

These tenets have hindered the adoption of reverse osmosis (RO) and other pressure-driven membrane technologies; thus, high volume desalination and chemical contaminant removal is nearly nonexistent in these scenarios. Pressure driven membrane systems including RO, nanofiltration (NF), and ultrafiltration (UF) all encounter significant maintenance requirements due to rapid fouling and scaling, lack of education in operation, and also have high energy requirements. Such systems have been demonstrated occasionally in development scenarios (e.g., Katadyn Spectra Maker models, Aspen 2000DM, Karcher WTC500/700; other organizations have made containerized systems including Mascara, Yemen Boreal Light, Somaliland RO, Aquasisstance, modified Veolia Aquaforce systems) but have significant capital cost due to the significant energy requirements and thus solar array size. The main concern of NGOs with photovoltaics in crises is the size of the array [16]. Pressure-drive membrane processes often fail in rapid deployment [17] due to their lack in mobility, need for highly specific feed water compositions, high maintenance and consumables.

Current BWT systems aim to treat turbidity and then chlorinate but rely on sources of surface and groundwater that are absent of chemical contaminants. Such systems for high volume water treatment often include rapid pressure-sand filters driven by diesel pumps. Reliance on diesel for power is becoming an increasing concern in disasters and especially conflict regions where supply chains may be cut off or the price of diesel may be cost prohibitive [18]. Even outside emergency scenarios, remote and developing areas would benefit greatly from the use of renewables such as solar or wind power; renewables decentralize power distribution, can create simpler supply chains, and are important tools for mitigating global climate change. Developing regions of the world are predicted to contribute significantly to the global population (with over half of the global population increase projected attributed to Sub-Saharan Africa [19, 20]) and this increase in demand, especially in energy, has high potential to augment carbon emissions [21]; Hence, the integration of sustainable energy and practices in developing economies is crucial.

1.2 The potential for simple, batteryless, off-grid desalination using electrodialysis

Electrodialysis reversal (EDR) is a desalination technology that is well-suited to meet the aforementioned needs. It has been studied and iterated upon for many years, with applications in areas from sewage treatment to whey extraction from milk [22]. This work proposes the usage of photovoltaic electrodialysis as a technology that is well-suited for a robust, deployable desalination scenario. Electrodialysis is energy and water efficient, can handle feedwater streams of varying concentration and compositions, can intake higher turbidity feedwater, has significant operational flexibility, and is cost competitive with on-grid reverse osmosis systems in treatment of brackish water [23, 24]. The high energy efficiency and flexibility make electrodialysis well suited for operation with renewable energy (e.g., solar). The modeling, design and performance of electrodialysis desalination systems have been documented significantly in literature [25–28].

1.3 Time-variant batch electrodialysis operation and areas for improvement

A system directly powered from a variable energy source such as solar does not have significant energy storage, and in most electrically-driven hardware, this implies the system is batteryless. The aim of a direct-drive (batteryless) desalination system is to maximally desalinate with all of the immediately available power. Typical control schemes for desalination include either constant current or constant voltage operation [29]. A study of constant voltage versus constant current operation (under conditions of controlled flow rate and feed salinity in batch operation) concluded that constant current is always energetically better than constant voltage operation [30], mainly due to the tracking of stack resistance over time. In contrast, time-variant theory previously developed further supports and leverages this scheme (where voltage is being varied to adjust to resistance changes) [31]. The aims of direct-drive desalination have been approached in prior art using time-variant theory [32, 33].

Time-variant electrodialysis theory involves independently varying flow rate and voltage over time to most efficiently desalinate while utilizing all the available solar irradiance. Determining the flow rate and voltage that maximizes desalination is highly non-trivial. Le Hénaff et al. 2019 [32] and He et al. 2021 [33] demonstrated this time-variant theory using a purely model based controller and had accomplished this optimally in simulation, but were unable to operate in practice purely on solar power - they still required significant battery storage capacity (some of which was assumed in their design). Furthermore, the Le Hénaff et al. 2019 encountered overdrawing issues on startup which would trip-off the system. Conforti modified this direct-drive controller to adjust for overshoot by altering the calculation of stack resistance and Connors et al. 2021 demonstrated the overdrawing issue was fixed [23]. However, numerous practical issues for direct-drive electrodialysis still persist.

One problem is that the system consumes significant battery power because the controller is unable to account for the variable hotel load of the latent components. Hotel load is often referred to in vehicle transport systems and is known as the electrical load caused by all systems other than for propulsion; in our case, it is the electrical load of all systems other than for desalination (i.e., pump motors, electrodialysis stack power supply). Another problem includes a clash between practical computation speed and the significant computational requirements of the model-based controller, which relies on a model of stack resistance and iterative loops. Coupling numerous models can cause significant error propagation and such models require adjustments to their fit parameters as the system changes and degrades over time. Finally, the iterative solver within this model-based controller was at times, unable to produce a solution for the optimum flow rate and voltage distribution within a practically reasonable time; response that is too slow relative to solar irradiance fluctuations requires significant energy storage.

Hence, a direct-drive (batteryless) electrodialysis desalination system has never been fully demonstrated in implementation. The theory for the design of a batteryless system and demonstration of it in practice has yet to be fully realized. The design of such a system is a piece that is key to meeting the needs entailed by humanitarian emergencies, and robustness required in remote, resource-constrained communities.

The research aims for this work are as follows:

1. Explore the needs of desalination in humanitarian crises.

2. Create and articulate a direct-drive control scheme that minimizes energy storage in practice, is computationally robust, and maximizes water production rate.

3. Experimentally demonstrate this technology performs in authentic physical conditions (i.e., real solar irradiance and brackish groundwater) to validate controller reliability and functionality on minimal energy capacity.

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Chapter 2

Background: The need for desalination in humanitarian crises

This chapter provides background for the need for desalination in humanitarian scenarios and in broader contexts of global development.

2.1 Summary

Humanitarian crises ranging from political unrest to natural disasters are becoming increasingly prevalent with global climate change. Correspondingly, there are an increasing number of regions that consist both of high crises risk and saline water contamination. Such regions include the Middle East, Subsaharan Africa (particularly along the Great Rift Valley), Southeast Asia (including the Mekong Delta and Pacific Islands), and coastal regions. However, there is a lack of robust, deployable desalination technologies for humanitarian crises. This is mainly attributed to the highly-constrained environment which necessitate: minimization of consumables, rapid speed of deployment and simplification of operation and maintenance. Such constraints are often secondary thoughts, are difficult to traditionally quantify, and differ from stable commercial situations where operations are supported by an accessible supply chain and network of technicians. These barriers have particularly hindered the adoption of membrane technology and thus, high volume desalination and chemical contaminant removal. This chapter justifies the need for desalination technology in humanitarian crises via geospatial analysis of saline water databases and exploration of regional case studies, formulates design requirements for an emergency-use desalination system based on needs extracted from open-interviews of stakeholders and literature review, evaluates some of the gaps within currently employed deployable desalination systems and explores the potential opportunities of other desalination technology.

2.2 Primer

The usage of desalination and chemical treatment in the context of humanitarian crises is a fairly unexplored space. There are some technologies adopted from use in other contexts such as military water treatment units that are periodically deployed in emergencies. However, the importance of desalination in humanitarian emergencies is not well understood. Furthermore, the existing solutions and decision making processes that practitioners and humanitarian aid organizations utilize are not designed for desalination and chemical treatment. Finally, the design requirements and an investigation of potentially viable desalination and chemical treatment technologies for usage in humanitarian emergencies has not been explored in depth.

Through literature review, geospatial data analysis, technoeconomic analysis, and through semi-structured interviews of practitioners, this chapter aims to:

1. Explore the need space for desalination in humanitarian crises.

2. Review the currently employed solutions and decision making processes.

3. Characterize a generalized set of design requirements for a desalination system designed specifically for humanitarian deployment.

4. Briefly examine the trade-offs and potential of existing desalination technology in the context of these requirements.

2.3 Methods

To understand if there is a need for desalination in humanitarian emergencies, what the current solutions are, and what potential solutions may exist, non-systematic literature review and technoeconomic analysis was conducted. For understanding the geographic need for desalination in humanitarian emergencies in particular, geospatial data analysis and correlation was conducted between metrics for groundwater salinization and the prevalence of natural disasters and/or conflict.

This exploratory research involved a focused literature review conducted by the researchers using a number of water, sanitation and hygiene (WASH) cluster databases with keywords including items that pertained to the general topics of bulk water treatment, WASH interventions, chemical treatment and desalination. Some of database and publishers the authors found had high relevance include Relief Web, Joint Monitoring Programme, Practical Action Publishing's Waterlines, Assessment Capacities Project (ACAPS), United States Agency for International Development (US AID) Humanitarian Library, various NGO databases (ICRC Resource Centre, Oxfam Research and Publications), and various United Nations (UN) databases (WASH UNHCR Database, UNICEF Data and Reports, UN OCHA Center for Humanitarian Data, UNDRR Prevention Web - many of these organizations' acronyms will be defined in practical context in later sections of this work). Additional gray and unpublished literature from experts and practitioners were also incorporated and considered. In future work, systematic review protocol could identify some literature that was absent from this study.

To determine a generalized set of design requirements for potential desalination systems in humanitarian crises, interviews with WASH experts and practitioners were conducted. The interviews were in a semi-structured format with a list of general guiding questions designed to elucidate needs of the practitioner, the overarching organization, and beneficiaries. However, while these questions formed the basis for beginning the interview, the interviews were allowed to digress into detail on the practitioners' areas of concern or interest. Notes and quotations from the interviews were coded using a quick and simple, flat inductive coding frame. The overarching themes that arose were divided into requirements categories and subcategories. Generalized metrics were determined and assigned with the assistance of literature, guidelines, and these interviews. It should be noted that a larger interview sample size and other coding methods such as with automated natural language processing tools could be explored in later work - this design requirements explication is rather preliminary but creates a foundation for future investigation.

2.4 Humanitarian Crises

2.4.1 Water in humanitarian response

In emergencies, a minimum of 7.5 liters of water per person per day is recommended [1], with 3-4 liters per day necessary for survival depending on climate conditions [2]. A natural disaster, political instability and many other types of emergencies can cause immediate disruption of water supply and treatment. Hurricanes destroy infrastructure, warring parties pollute drinking wells of the opposition, persecution can push migrants to unfamiliar territory with a lack of accessible and potable water. One reference of widely agreed upon standards for humanitarian response is the Sphere Handbook [3].

International organizations, local non-governmental organizations (NGOs), and individual governments are a few significant stakeholders which provide monetary and physical aid [4]. Some prominent examples of aid organizations and stakeholders involved in WASH include the United Nations International Children's Emergency Fund (UNICEF), Oxfam, Médecins Sans Frontières (MSF) and the International Federation/Committee of the Red Cross and Red Crescent (IFRC/ICRC).

Crises with multiple agency involvement are typically coordinated by the Inter-Agency Standing Committee (IASC), a forum under the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA). While forecasts anticipating natural disasters exist, immediate responses to large crises that warrant international coordination are initiated based on rapid needs assessment (e.g. Flash Appeals) within 3-5 days. These reports incorporate metrics such as predicted amount of beneficiaries [5, 6]. Responses later shift to increased specificity of strategy and monitoring. In general, phases of a crisis include emergency/acute response (< 3 months), protracted crisis (> 3 months to years) and long-term/development interventions (multiple years) [7]. The IASC delegates projects and specific targets for involved organizations, which flow down into various aid subsectors referred to as United Nations clusters [8]. These clusters are overseen by various UN organizations (e.g. the Water, Sanitation and Hygiene (WASH) cluster is supervised by UNICEF, the Health cluster by the World Health Organization (WHO), and Food Security by the World Food Programme (WFP) and Food and Agriculture Organization (FAO)). Acute intervention strategies within the WASH cluster commonly include rapid distribution (e.g. tanker truck, bladders, bottled), rudimentary treatment of water, and packaged kits. Targeted interventions to rehabilitate and provide sustainable sources, distribution, and treatment are developed over time based on context (examples of recent intervention plans include [9–11]). The general process for contemporary United Nations crisis response architecture and actions are well-detailed in [12].

2.4.2 Archetypes and intervention structure

Crises are generally categorized, but not limited to, the ontology seen in Fig. 2-1 [13]. However, humanitarian responses are often broken down into three colloquial categories: (1) natural disasters, (2) outbreaks and (3) complex emergencies. Complex emergencies often encompass conflict regions and lead to migration of refugees or internally displaced persons (IDPs) but also may refer to situations where multiple emergencies are ongoing; for instance, the 2010 earthquake in Haiti which eventually was coupled with a Cholera outbreak.

Note, a refugee is defined as an individual who has crossed an international borders to flee persecution, war, violence, or conflict. An internally displaced person is an individual displaced within their own country. A migrant is an ill-defined umbrella term that refers to individuals travelling from their origin country for any other reason,

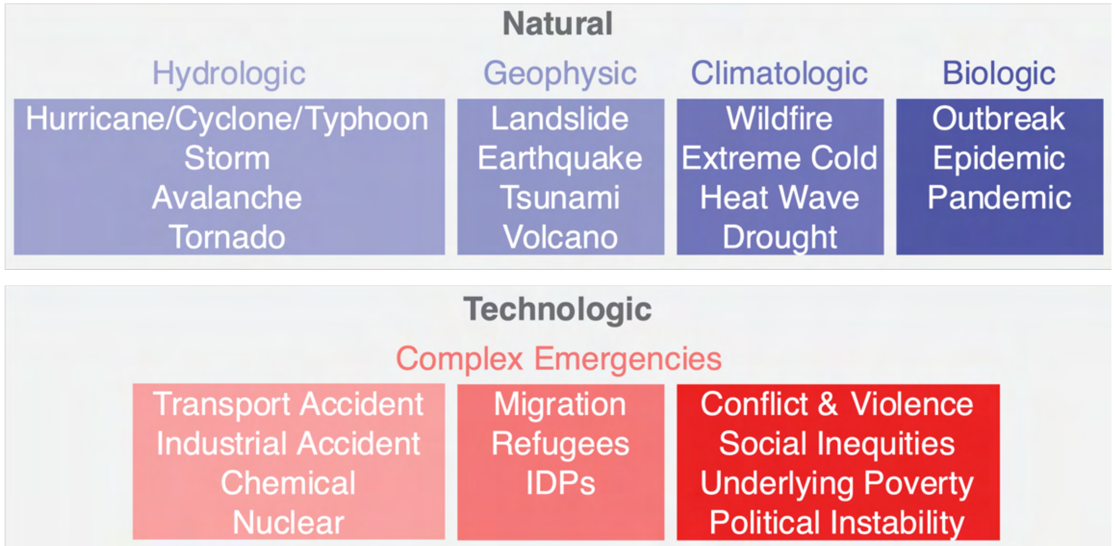

Figure 2-1: Ontology of crises

such as fleeing poverty for employment.

WASH emergency response is highly specific to situational context. In an ideal setting, water treatment is tuned specific contaminants, knowledge of source locations, specific populations who require intervention, the distribution of these populations, local supply chain and accessible infrastructure. In acute emergencies, this knowledge is highly-constrained. Thus, it is fundamental for WASH interventions to be flexible to a wide array of contexts.

Despite contextual limitations, the geographic distribution and quantity of the population affected are one of a number of metrics often estimated in early response reporting. From this, general WASH archetypes somewhat agnostic to the category of emergency can be created (Fig. 2-2). General guidelines for developing needs assessments include [14, 15] as well as exist within organizations such as the Assessment Capacities Project.

Emergencies with sparse populations are characterized by a geographically-widespread population distribution in groupings that are less than the thousands. These may involve disasters or crises occurring in rural settings or can involve small mobile populations. For instance, refugees, IDPs, or migrants fleeing regions of political instability or poverty. In acute-sparse emergencies, it is often challenging to logistically

		Acute	Protracted	Long-term/Recovery
Sparse		Rural flood, outbreak, migrants	Violent conflict, political instability	Resettlement
		HWT, delivery	Source rehabilitation & creation, HWT	Source rehabilitation and creation, HWT
Dense		City flooding, earthquake	Conflict leading to refugee or IDP camp, drought	City reconstruction
		Simple BWT (1-2 m^3/hr), delivery	Batch or BWT (2-10 m^3/hr)	Customized scheme

Figure 2-2: WASH Archetypes and common interventions

provide resources and interventions due to unreliable supply chains and damaged or nonexistent infrastructure to access dispersed populations. If existing sources are damaged, water delivery most commonly via trucking initially occurs, infrastructure permitting. Delivery of household water treatment (HWT) interventions, such as coagulant-flocculant sachets, chlorine tablets, and small filters is also considered, typically delivered as WASH packages which may include items such as soap, buckets, flashlights, cloth, sanitary pads, detergent, educational guides, etc. [16]. HWTs are particularly effective in rural scenarios in low and middle income countries [17]. As the emergency continues over time, rehabilitation of preexisting water sources or creation of new sources often occurs (such as via bore well drilling) [7, 18].

Groupings of population densities of 300 inhabitants per km^2 with a population of at least 5,000 in the cluster are considered an urban cluster by the UN Statistical Commission [19]. Interventions for these relatively dense clusters again include transporting water and/or a range of bulk water treatment (BWT) schemes which systems that produce relatively high volumes of water (approximately $> 1\ m^3/hr$). Natural disasters such as hurricanes, tsunamis, and typhoons often cause rapid flooding and create acute emergencies in population dense regions. Examples of acute, population dense emergencies include flooding in Pakistan in 2010 and the tsunami in Indonesia 2009 where both bulk and small-scale water treatment units were employed [2]. Earthquakes, such as in Haiti 2010 or conflict such as the bombing of Aleppo, Syria in 2012 involved protracted (11 months and 19 months respectively) interventions where sedimentation tank water treatment systems were employed, alongside

WASH packages, water trucking, well restoration and local wastewater treatment plant (WWTP) and drinking water treatment plant (DWTP) reconstruction [20]. Over time, rehabilitation-focused interventions become more important and may range from fuel distribution, solarization, well digging and drilling, and operational support of water facilities [10]. While capacity building is an increasingly advocated facet in emergency response, it is not always an aim. Responding NGOs often leave recovery to beneficiaries once a state of stability has been reached [21–23].

Detailed decision making trees for water treatment interventions are outlined differently depending on the intervening organization, but have commonality in two major aims (1) removal of turbidity, and (2) biological disinfection. Turbidity is a measurement of suspended and dissolved matter and is used to assess the health of water bodies [24]. It is most commonly measured in units of nephrological turbidity units (NTU) and is detected via nephelometry or light scattering (USEPA Method 180.1 or ISO 7027). High turbidity hinders the effectiveness of the most common disinfection method in crises: chlorination [25, 26].

There is generally agreement amongst most water quality thresholds and decision making processes within WASH organizations, however some include more or less detail with less common scenarios such as chemical contamination. Figure 2-3 details water treatment strategies in crises which the authors developed based on coalescing decision making processes from a number of guidelines and handbooks [3, 27–34].

This decision tree is broken down into three stages: treatment of chemicals, of physical particulate, and of biological contaminants. They commonly occur in this order. In chemical treatment, current practices consider Fluoride (Fl) concentration greater than 1.5 mg/L as potentially hazardous but safe to drink in an emergency scenario. Iron (Fe) levels above 5 mg/L should be aerated for removal (though United States Environmental Protection Agency recommendations are $< 0.3\ mg/L$). Salinity however has no treatment mechanism if the quality is unacceptable - practitioners are told to find an alternative water source. Once chemicals are treated, the focus shifts to removing physical particulate if above 20 NTU using either home or bulk water treatment schemes. Then, when the turbidity is below 5 NTU, the water is disinfected

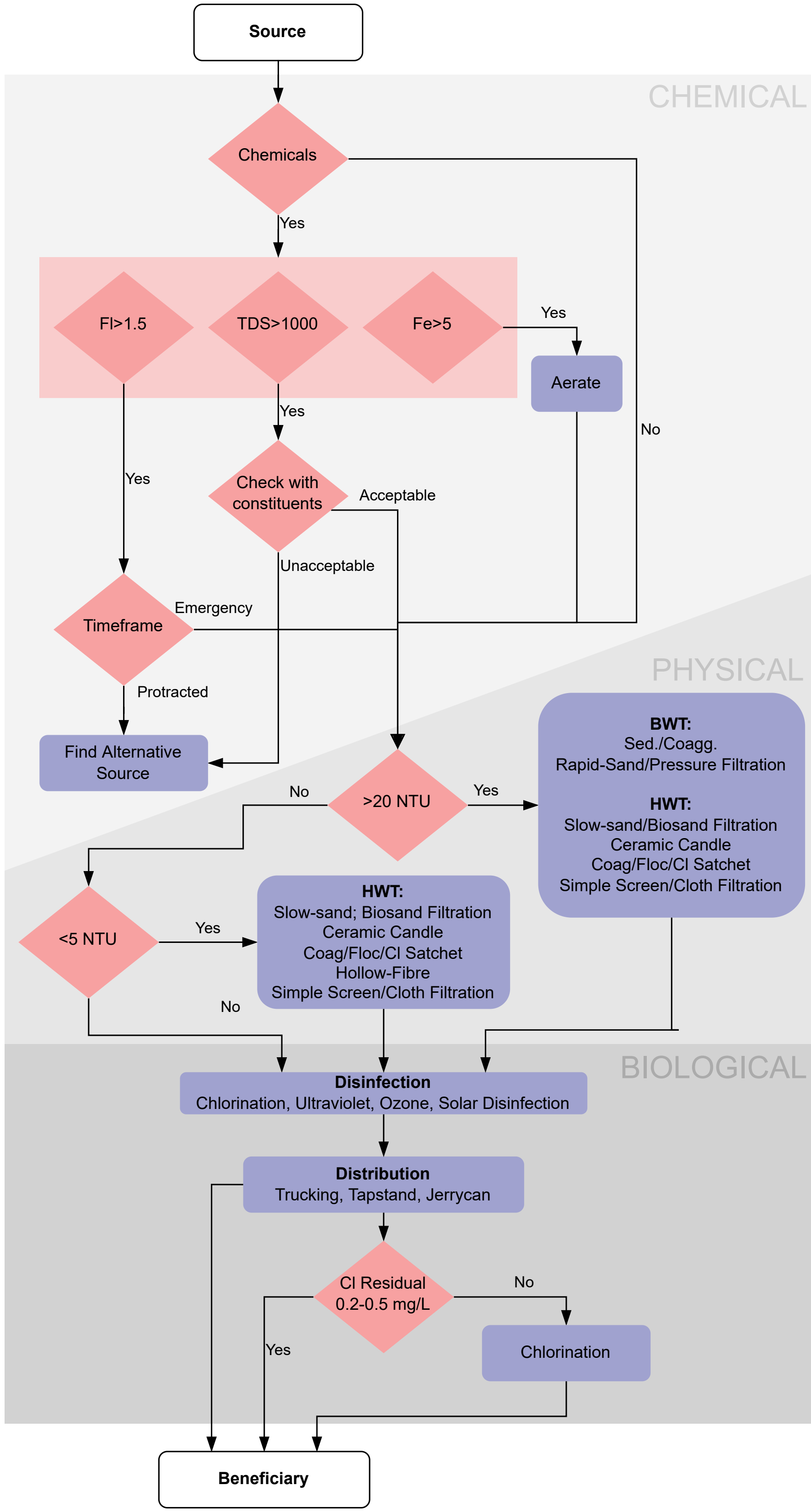

Figure 2-3: Generalized WASH intervention decision-tree in emergencies

most commonly via chlorination, distributed, and then sometimes re-chlorinated if the residual is low.

One example could be that the water source is a river, absent of chemicals, which contains some turbidity above 20 NTU. This water source could then be subjected to sedimentation and coaggulation (labeled sed./coagg. in Fig. 2-3) in large tanks and then disinfected via calcium hypochlorite powder. Another instance though could be that practitioners encounter a saline borehole in an arid environment desolate of other water sources; users may reject this water due to high salinity. Practitioners are then instructed to find an alternative source (because the treatment mechanisms are not present), however, they may not be able to find another source.

While this decision tree describes multiple strategies for removing physical particulate and disinfecting biological contaminants, there are currently no commonly employed, standardized, or well-agreed upon methodologies for treating chemical contaminants including salinity [35]. Operators are instructed to avoid sources contaminated with high salinity or unacceptable levels of chemicals such as nitrates, heavy metals, and arsenic. Relatively low concentration of chemical contaminants can cause long-term health issues and thus are not of principal concern in emergency water treatment but are growing factors of importance in long-term development. Drinking saline water over a period of time is linked to numerous adverse health effects including cardiovascular diseases, gastrointestinal disease, dermatological disease, acute respiratory infections, and miscarriages [36, 37]. However even in acute emergencies, salinity can cause operators to avoid and beneficiaries to reject otherwise satisfactory water sources.

2.5 Salininty in emergencies

Desalination is a relatively unexplored element of humanitarian emergencies. When dealing with the treatment of saline waters in emergencies, current procedures for prominent international agencies such as MSF [33], UNICEF [34], and Oxfam [28] simply instruct aid workers to avoid saline sources (Fig. 2-3. Lack of saline water treatment protocol is prevalent not only in acute emergencies (3-6 weeks) but also exists even in protracted emergencies (months) and into long-term recovery and development periods. It also is more broadly, a growing chronic issue as a form of groundwater contamination.

Crises where saline contaminants may become prevalent water sources include tsunamis, flooding (about 42% of natural disasters), seawater intrusion [7], desertification, drought, and chemical contaminants are often used in conflict driven sabotage of water bodies. With approximately 40% of the world population living within 150 km of the coast [38] and high frequency of flooding, drought, extreme weather, and sea-level events affecting this population (relative to other natural disasters) [39, 40], these regions are increasingly susceptible to saline water intrusion and saline water treatment will become increasingly relevant in response and in global health development. Unfortunately, little if any data or literature currently exists on understanding the prevalence of salinity in different crisis archetypes, so forecasting the scale of the problem is non-trivial. Nevertheless, there have been a number of calls for desalination systems from humanitarian groups, including Oxfam [41–43] and a recent discussion of treatment systems for desalination in emergencies hosted by the Red Cross [44].

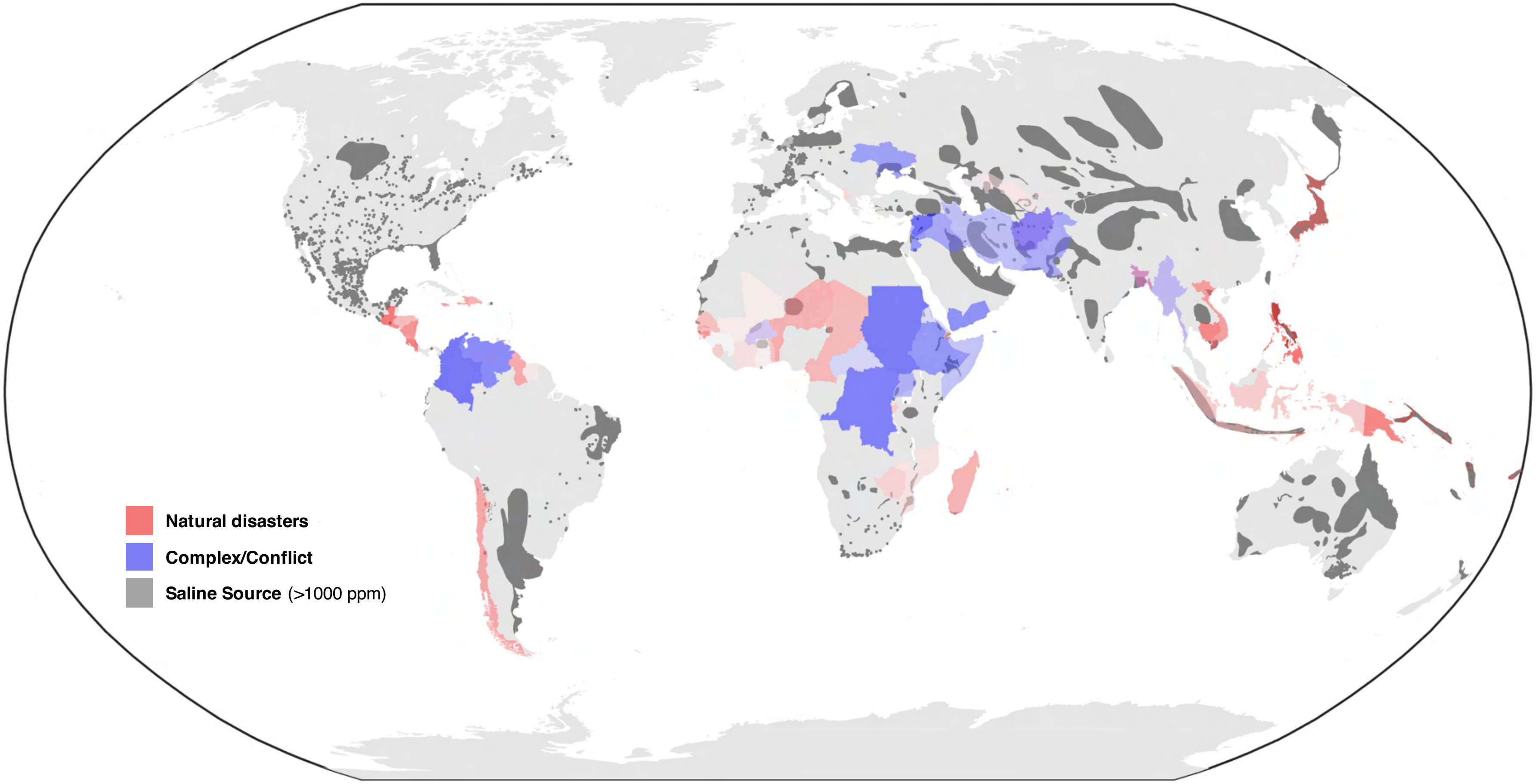

Figure 2-4: Global crises and salinity map

To understand the potential scope of salinity in humanitarian crises, the authors examined known databases of high salinity groundwater aquifers [45–48]. It is noted that multiple regions of high groundwater salinity overlap with areas that are susceptible to disasters [49–51] and have history of conflict [52, 53] (Fig. 2-4). This indicates that many of their potential water sources may already have saline contaminants. These regions also correspond to regions projected to experience decreases in precipitation as a result of climate change, which will exacerbate the lack of non-saline surface and groundwater [54–56]. There are noticeable gaps in water salinity and composition data due to cost; some groups are attempting to alleviate this issue by developing low cost conductivity sensors [57].

These regions of note can be generalized into the Middle East, Sub-Saharan Africa, and Southeast Asia, and these regions have also been noted as regions of concern in literature [58]. However, it should be noted as far as inland Southeast and Western United States there are increasing cases of saline aquifers. There are some naturally occurring saline aquifers due to geologic formation (connate) but many aquifers are experiencing rapid increases in rates of salinization due to rising sea levels and withdrawal from wells; overdrawing groundwater from wells can intensify saline intrusion by exacerbating the pressure differential between seawater and lower water tables [59–61]. The USGS published a comprehensive report which outlines the scope of brackish groundwater in the United States [62].

In the Middle East, there are many cases where desalination has become increasingly prevalent. Palestine is one example within the Middle East where a reliance on desalination has developed due to its supply chain isolation [63]. Nitrates, heavy-metals and other chemicals are also present due to wastewater leeching, unreliable power, and excess pumping [64]. Syria, Lebanon, and Jordan experience high salinity in both surface water and aquifers linked to over exploitation from irrigation [65] and an influx of water demand from refugees [66–68]. Yemen experiences extremely high salinity surface water (up to deciSiemens [69]) and saline groundwater again due to seawater intrusion and its arid climate [70]. Many of these regions unfortunately have been historically subject to conflict and are ranked high risk in terms of political instability [71]. Refugee camps including Zaatari in Jordan [72] and Domiz in Iraq [73] have reported saline water contamination. Beneficiaries have been reported to avoid treated water and seek other nearby surface water sources which are untreated and often contaminated with harmful organisms and bacteria (e.g. Escherichia coli) due to taste preferences [3]; such practices have been observed across agencies with some beneficiaries even rejecting food [74]. UNICEF constructed a partially solar powered reverse osmosis plant (producing 20,000 m^3/day) in Palestine to mitigate these water shortages and compensate for unreliable grid power [75].

In Southeast Asia and the Indo-West Pacific, increasing amounts of seawater intrusion are present in soil and drinking water. In Bangladesh average tubewell salinities of 915 mg/L have been reported [76] and have been shown to cause severe illness [36]. The Mekong Delta including Vietnam has become increasingly prone to saline intrusion due to drought and seasonal water shortages [77, 78], which have also caused agricultural losses affecting upwards of 1 million people [79]. Indonesia [80], the Philippines [81] and Papua New Guinea all [82] report saline groundwater aquifers and an increased reliance on bottled water and rainwater catchment; a supply chain interruption due to disaster or conflict would create a major disruption to this drinking water supply. Rainwater catchment in general is quite common in island nations [83], however cases exist where brackish groundwater is desalinated using membrane processes (e.g. Canary Islands [84]).

In Africa, there have been an influx of reports of saline groundwater in multiple areas of the continent. In East Africa, groundwater scarcity and saline intrusion are exacerbated by a deep water table, the arid climate, volcanic and geothermal activity [85, 86]. Some specific examples of countries with recent conflict and reports of a need for saline and chemical treatment include Somalia [87] and Sudan [88]. They report surface water higher in salt concentration than groundwater; some suggest drilling deeper for less saline water in this region [89]. One instance of acute response noted the potential need for saline water treatment in Mozambique in the aftermath of Cyclone Idai [90] and subsequent efforts have been made to map seawater intrusion [91, 92]. At the Kakuma and Dadaab refugee camps in Kenya, increasing groundwater salinity has been noticed, especially over periods of drought [93, 94]. Similarly, reverse osmosis plants have been recommended for use at Sahrawi in Algeria [95]. Coastal regions of Kenya including Kwale County have had increasing desire for community scale desalination systems for water security and economic development [96]. Other prominent issues of broader chemical contamination include fluoride in Tanzania and heavy metals that leech from mines in the Democratic Republic of the Congo.

Central and Latin America have some reports of brackish water concerns, including the countries of Belize, Nicaragua, and Peru [97].

These are just some of the many regions that are currently affected, and could be affected by the need for desalination in humanitarian crises and development. When a region's nominal water sources experience shortages or damage from natural disasters such as drought or storms, or even isolation due to conflict, saline water bodies will more frequently become the only available source of water.

2.6 System Design Requirements

2.6.1 Interviews and requirements extraction

Eighteen practitioners, academics, and engineers from MSF, UNICEF, ICRC, IFRC and with experience in WASH were interviewed in a semi-structured interview format and needs statements and attributes were extracted. These statements were then codified and related to a proposed set of generalized design requirements, discussed in depth below.

Generalized requirements for BWTs are most practically defined for acute emergencies. Protracted emergencies often have more flexible, situation specific design opportunities which are often focused on rehabilitation, sustainability, and capacity building. Requirements for BWTs in acute emergencies can be broken down into the categories listed below. However, many of these requirements for this design scheme are useful to consider in broader applications. The requirements defined in Table 2.1 reflect constraints and do not show the relative importance of each factor; the prioritization of one criterion over another depends greatly on the operational context and is difficult to generalize, but could be considered in future work or in specific case studies.

Criterion	**Requirement**
	Quantity
Flow Rate	(1 L/hr)/person [98]; typically 1 to 10 m^3/hr [90]
Produced Water	2.5-3 L for survival, 7.5-15 L for total basic per person [3]
	Quality
Biological	$> 0.2 - 0.5$ mg/L FCR, $<$ 10 CFU/100 mL [3, 30, 33]
Physical	$<$ 20 NTU; ideally $<$ 5 NTU [3, 27, 32, 33]
Chemical	desalinate any input to $<$ 1000 ppm [28, 99, 100]
Radiological	$< 100mSv$ in acute scenario, <0.1 per year long-term [99]
Color	transmittance $<$ 15 color units [101]
Smell	$<$ 3 TON (threshold odor number) [101]
	Transport
Weight	$<$ 1500 kg for Euro pallet/ISO1; <8,000 lbs for trailered SUV [90, 102]
Volume	$< 2.09m^3$ Euro pallet/ISO1
Number of containers	1 to 2 containers [103]
Regulations	hazardous materials adhere to ISO and IATA standards [102]
	Cost
CAPEX	$2800 - 4500$ USD / (m^3/hr) [16, 104–106]
OPEX	1.25-2.5 USD/m^3 [16, 104–106]

	Maintenance
Replacement frequency	none within 3 weeks [106]
Waste: brine quantity	< 40% of the total feed [90]
Back-washing frequency	minimize [106–108]
Maintenance time	< 3 hrs/day
	Operation
Operator Training	1 day or less [90, 109]
Set-Up	2-3 hrs, maximum 2 days for complex surface water treatment [103]
Flexibility	can be shipped as a unit or taken in parts [90, 103]
User ease of participation	< 500 m from a tap, < 250 people per tap, < 30 mins queue time [3, 110]
Operating time	8+ hours per day
	Reliability
Wind Speed	up to 74 mph
Humidity	$0 - 100\%$
Temperature	$+/-$ 40 deg. Celsius
Pressure	$69.7 - 108.38$ kPa
Security	avoids sabotage [111, 112]

Table 2.1: Desalination BWT Requirements

2.6.2 Quantity

In acute emergencies, it is best to maximize quantity of water while preserving a minimum threshold water quality. In other words, it is better to have a high quantity of lower quality water than a low quantity of the highest quality water. Existing BWT system production rates range from 1 m^3 to 10 m^3/hr of treated water [2, 35, 113]. As the emergency extends, this quantity must eventually reach WHO and/or Sphere standards. However, these standards in practice are often adjusted depending on the assessment of the nominal or baseline country state. For instance, a country nominally with a 15 CFU/100 mL of Escherichia Coli concentration is already exceeding the WHO/Sphere standard for drinking water- however, an NGO might aim to reach that nominal state again rather than aim for the standard in an emergency.

To achieve quantity, large sedimentation tanks or bladders are constructed (especially near dense, static populations) with chlorine dosing. Water tankers may transport nearby surface water to refugee camps for the purpose of maximizing quantity initially (often times this surface water may even be contaminated). Trucks may have been previously used for fuel and not properly sanitized. Chlorine dosing might be inconsistent and not well monitored [114]. These examples show prioritization in the acute phase on quantity over quality.

2.6.3 Quality

However, there are typically minimum thresholds for water quality even in acute emergencies with metrics predominantly associated with health and with user acceptability. The water quality metrics associated with health are most commonly turbidity and free chlorine residual. Typical turbidity targets are $< 5 - 10$ NTU and targets for free chlorine residual (FCR) are 2.5-5 mg/L in emergencies [3, 33]. As the reader may recall, reducing turbidity is an aim for effective chlorination and thus elimination of biological pathogens which often include but are not limited to Escherichia coli, Cryptosporidium, Salmonella Typhi, and Giardia. Diarrheal disease and malnutrition are the leading causes of death these contexts [115].

Chemical and radiological [99] contaminants such as arsenic, fluoride, lead, and other heavy metals are less commonly tested and almost never treated (simply avoided) in acute emergencies but are still important factors. Other quality metrics typically associated with user acceptance include salinity, color, and smell. A salinity threshold of $< 200 - 250$ mg/L of sodium and chloride ions is a common health guideline from the WHO [116]. In emergencies, acceptable salinity thresholds are approximately $<$ 1000 mg/L [28] and have even been accepted as standard levels in some regions with chronic saline water problems [100, 117]. However, salinity often follows user taste preferences specific to the geographic area; for instance, some regions of India have taste palates that are most commonly $< 200 - 500$ ppm [118] because they are accustomed to reverse osmosis treated water. In some regions of Africa, beneficiaries will resolve the problem of saline taste by diluting water with milk [106].

Color and smell are additional factors which can dissuade user acceptance [101] because beneficiaries believe the water is unclean, or even culturally inappropriate. Users may seek alternative sources which may appear in higher quality but are actually more dangerous in composition.

2.6.4 Cost

The cost of humanitarian aid ranges greatly, with an example of total annual humanitarian expenditure per capita in 2017 ranging from $2.5 USD in Burkina Faso to $75 in Jordan [119]; much of this is attributed to factors such as differences in the number of humanitarian aid organizations in the region, geopolitical importance, and quantity of refugees (Jordan had approximately 33 times the amount of refugees than Burkina Faso). The funding allocated to the WASH cluster in particular also varies greatly depending on the forecasts and situational assessments of demand. A typical cost threshold for bulk water treatment devices is non-trivial and highly dependent on the emergency and purchasing organization or entity. From the perspective of designing a device to be used specifically by international NGOs and operated by deployed practitioners, the cost per m^3/hr of water for historically employed packaged water systems is approximately $2800-4500 USD. These packaged water systems were designed for the removal of turbidity and chlorination - none of the systems deployed are designed to treat chemicals including salinity. Because of the complexity of operation and high cost, UNICEF claims membrane processes are generally not appropriate for use in developing countries [30]. The current low perceived viability of membrane technology thus drastically reduces the quantity of treatable chemical or salt contaminated water.

2.6.5 Transport

Weight

Ease of transportation in unreliable supply chains is essential in crises. The weight of the system is one important characteristic, and should be less than 1500 kg to meet European pallet (ISO1) requirements. This requirement is driven by the maximum weight for a single pallet to be air shipped. Air shipment is the fastest and preferred method for immediate response in emergencies. The system weight should also be light enough to fit on a small 4x4 truck/SUV or at the greatest be trailered by such a vehicle [90]. Common vehicles used by the UN include Toyota Land Crusiers, Hilux, Prato, Land Rover Defenders, Nissan Patrol, and at times trucks (e.g., Renault) and busses (e.g., Volvo). Ideally, the system would be light enough to be lifted via a human crew; forklifts and heavy equipment are often unavailable [111]. Low weight caters well to flexibility - transport may need to be via rowboat, bush plane, and many other vehicle forms.

Volume

Similar to the weight requirement, the aim of volume is to be minimal for ease of shipment. However, an upper limit could be the volume and dimensions of a European pallet $< 2.09\ m^3$ or (31.5" x 47.24" x 77"). European pallets are smaller than United States standards and used broadly by the UN. Such a system that met this volume requirement would also fit well in ground and "last-mile" transit. The system could potentially be shipped as one, or in easy to assemble parts. Hoses are commonly reported as large space issues with high volume to weigh ratios in shipment.

Regulations

In interviews with UNICEF operators, batteries are mentioned to be an issue with shipment, maintenance, and reliability [102]. Lithium ion and energy storage devices in general (such as electric double-layer capacitor banks, which cover super and ultra-capacitors) of > 0.3 watt hours are subject to dangerous goods regulations (regulation UN3499). Depending on the type, weight, dimensions, capacity, and mode of transport, these regulations are more or less stringent [120]. These transportation standards vary depending on the international and/or national organizations involved and but are well outlined [121]. Recommendations against batteries were also found in literature due to their "high cost and short lifetime" [122]. Other items that historically report difficulty in shipment have included chlorine powder and diesel. There have been additional calls for some level of universal testing by independent organizations on bulk water treatment systems; this testing data could be used for system validation and serve as a metric of comparison for future BWTs [2].

2.6.6 Operation

While skilled operators are often used in large-scale BWT deployment by international NGOs, the aim of a system should be the simplest operation possible, such that the system can eventually be easily run by local users or technicians with minimal training. The best systems are "plug-and-play" with minimal operator maintenance. Operator training time should be minimal, but at max one day. The set up time for such systems should be on the scale of hours to a maximum of two days for complex surface water treatment and should be a similar level of time and simplicity (if the system is to be repacked) upon departure [90, 103, 109]. Service agreements between the local government and the intervening aid organization are also almost always necessary [111, 112]. Generally, the complexity of the system (i.e., number of components) should be minimized to aid not only in simple operation, but also in maintenance and reliability [2]. The ease of user participation must be high as well - standards exist quantifying the maximum distance from water taps and thus, the product water interface must be accessible and acceptable by users [110]. The system should have an operating time that is maximized throughout the day (8+ hours) with minimal downtime for cleaning and maintenance. Finally, the system should have flexibility; a system may need to be moved rapidly and redeployed to other environments as the situation develops. A system should also be capable of handling a variety of feed water and energetic conditions and still perform within a reasonable range of expectation. Modularity, adjustability, and multifunctionality are all important tenets that allow for the system to be adapted to a variety of scenarios and used for many different purposes by practitioners [90]. Flexibility also applies to a system that is adaptable throughout the timeline of an emergency, and which may even be used for capacity building in long-term scenarios (e.g., renewables for BWTs in the initial phase, and then evolving to street lighting for an IDP camp in the protracted time period).

Maintenance

Maintenance is considered by many practitioners to be "the largest issue" [90]. Another representative from ICRC claimed "the three main challenges are the people, the infrastructure, and the consumables" [103]. Maintenance can be quantified by metrics such as part replacement frequency (or amount of consumables and their lifetime), part availability, backwashing frequency, time, and level of skill required to service. Current systems employed at most rely on chemical consumables including disinfectants (calcium hypochlorite) and coagulants and flocculants (aluminum sulphate or "alum"), which are typically widely available locally [123]. The discharge or brine quantity from these systems are stronger areas of concern in protracted emergencies. However, in initial response brine disposal is not as important.

Finally, a reliance on diesel and oil in general as fuel sources for energy generation and pumping in water treatment is an increasing consumables challenge. Shipment of liquids is costly due to their weight, and despite the relatively high energy density of diesel, there have been increasing shortages which are greatly affecting humanitarian aid capabilities with examples in Syria [124], Venezuela [125], Ethiopia [126], Gaza [127] and more recently due to conflict in Ukraine. Fuel shortages are an important aspect of humanitarian logistics [128]. About 5% of humanitarian aid costs are attributed solely to generator repair and diesel fuel and countries in central Africa and some of the Middle East particularly experience unreliable supply and high diesel cost [119]. Solarization and use of other renewables are some currently explored routes to decrease reliance on diesel in protracted scenarios [98].

Reliability

Maintenance is closely tied to system reliability. The less reliable the system, the more time and resources spent on maintenance. A system's reliability can be quantified using a number of metrics including mean time to failure, mean time between failure, mean time to repair, lifetime, etc., but unfortunately these are not well characterized in currently deployed systems. Systems deployed in acute emergencies must be robust against numerous environmental factors including high wind speeds, variations in humidity (anywhere from arid climates to the saturation of a rain forest), and strong fluctuations in temperatures. Even perceptually warm climates such as Yemen have cold winter nights that may see temperatures below freezing and have caused emergency funding appeals for winterization plans in IDP and refugee populations [129]. Robustness of operation below freezing temperatures can be difficult for water treatment systems. Additionally, the system can be subjected to low temperatures and pressures in cargo holds during air transport. A deployed system may also face issues with security and potential for sabotage; warring parties have historically commandeered humanitarian aid from its original designation and used it as a tool for harm [130, 131] and have threatened the safety of health professionals and operators [132]. The potential for a resourced to be used in an ulterior fashion is a tenet designers of BWTs and humanitarian supplies must consider.

2.6.7 Risks and Limitations

While these requirements are generalized bulk water treatment system requirements that a desalination system should follow, there are limitations and context specific factors to consider. One important but mercurial requirement is the final product salinity. Acceptable taste preferences may significantly differ between separate social, cultural, and geographic areas; for instance, the acceptable salt threshold based on taste profiles in India differs from that of the United States and Canada (<81-800 ppm) [133]. Additionally, there are cases where these specific transportation metrics including weight and volume limitations may be more or less than the recommended values; in protracted scenarios, items may be shipped to ports where heavy off-loading equipment may exist alleviating the weight requirement. Operationally, there may be operators with the expertise to setup multiple containers and components. However, there are also many scenarios where systems may be setup and operated by local experts or in the long-term, the beneficiaries themselves, and thus simplicity and education is a greater concern. Furthermore, there may be some cases where consumables and maintenance may be more allowable. Deployments in regions that have reliable infrastructure may allow for more international or foreign replacement parts - though, a system could be best suited if it were compatible with locally available suppliers and many different product substitutes. Finally, a common difficulty faced with shipment of goods in humanitarian relief is understanding and adhering to local customs and government protocol; the UN logistics cluster (main affiliation within the WFP and under IASC) is well-suited and informed on current minutia. These rules may change the acceptability of system components. While the authors list ISO and IATA standards in the design requirements, the local considerations often carry equal or greater importance.

2.7 Existing Technology

Existing interventions can be broken down into bulk water treatment (BWT) and household water treatment (HWT) interventions. Literature exists that compares trade-offs between various BWT and HWT technologies; but, focus is primarily on currently employed technology. None of the current interventions cataloged by prominent WASH international aid organizations are able to treat chemical contaminants such as pesticides, heavy metals, or salinity. Generally, BWTs are appropriate for longer term, more permanent displacements and are great for high turbidity and more complex treatment. Often many low-cost units are better than a few high cost units. BWTs often lack independent testing standards, have been historically deployed in unnecessary areas, have high capital cost, require skilled operators, and require significant maintenance and downtime for cleaning [2]. HWTs have greater reach, are lower risk, have low short-term cost (but higher long-term cost), and provide point of consumption protection. However, they have a high risk of low utilization without proper education. Some useful reviews of BWT [134] and HWT methodologies include [7, 135] and a book on low-cost emergency water treatment [136]. While BWT and HWTs are commonly employed, the decision making process for their deployment is not well understood and process selection guidelines are not formulated in detail [137].

The International Federation of the Red Cross and Red Crescent, as well as the International Committee of the Red Cross/Crescent have historically used LMS, Berkefield, Scan, SETA, and other chlorine dosing systems [105] but many have not been employed in recent history [90]. Oxfam has one generalized water treatment unit in its catalog [104]. UNICEF also has a variety of water purification units, skids, and tanks [138]. MSF uses rapid pressure sand filtration units in two parallel channels which can be easily back washed [106]. Other purchasing perspectives include the potential for local governments and (in rare cases) beneficiaries to pre-purchase systems and use them nominally or store them "in case of emergency", however, household scale treatment and supplies are most commonly stored and distributed (rather than large systems).

Existing technology for desalination most commonly involves thermal distillation at the home-scale (e.g., boiling water, solar distillation) and reverse osmosis membrane processes in community to large-scale systems. Low-cost home-scale distillation provides little quantity and often does not meet demand [139]. Some cases exist of utilizing forward osmosis for desalination and purification [140] but current solvent packets are typically cost prohibitive. Reverse osmosis processes involve high maintenance, operator knowledge, and require significant pretreatment of feedwater (and thus consumables) - all of which are commonly challenging limitations in emergency response. Point of use reverse osmosis systems have been attempted in Gaza but failed due to rapid membrane clogging and lack of user education [63]. Atmospheric condensation has been implemented by some companies in disasters (e.g., Genaq, Watergen), which boasts the lack of prefiltration and typically includes only air filters as consumables. However, the technology has low production rates relative to its energy consumption, especially in low humidity environments. There are few examples of desalination systems specifically designed for humanitarian relief.

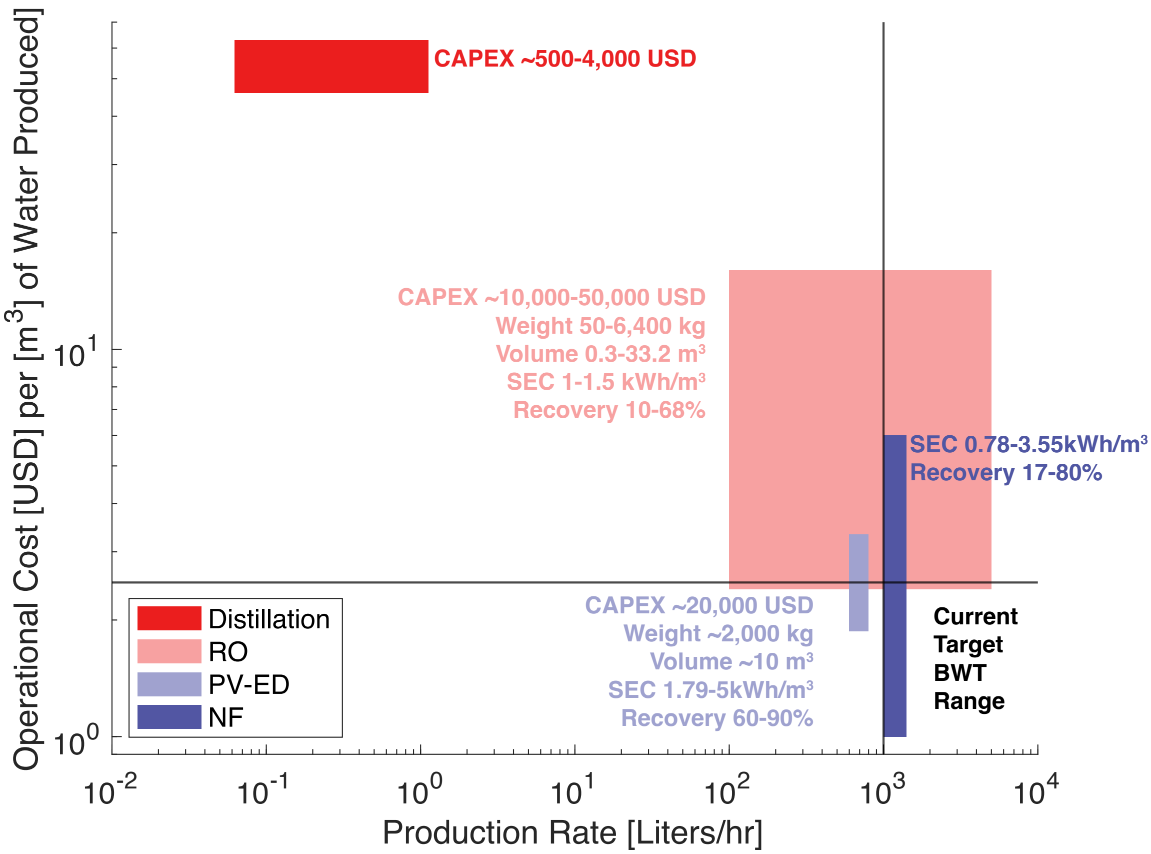

Figure 2-5: Evaluation of the operating cost versus production of current desalination systems

Four common desalination technologies are compared in Figure 2-5 based on their operating cost and production rates. Sources of costs and production rates used to generate this plot include [139, 141], for distillation, [142–152] for RO, [150] for PV-ED, and [153–159] for NF. The graph is in log-log scale to fully display the range of operation. Additional ranges of metrics - such as specific energy consumption (SEC) - from these studies are also displayed. Reverse osmosis, due to its history of employment has a variety of operating cases and associated costs, with some instances of photovoltaic operation [149]. Electrodialysis and nanofiltration have been explored less frequently in deployable scenarios and have less of a range of examples.

Notice, there is a significant operational cost gap between distillation and membrane technologies, likely associated with the significant energy consumption differences.

2.7.1 Nanofiltration

Nanofiltration (NF) is a pressure-driven membrane technology that utilizes pores slightly larger than reverse osmosis membranes, and thus is less prone to clogging (relative to reverse osmosis). It can be utilized for partial desalination (ranging from 20 to 80% [155, 157, 159]), and is especially effective against divalent ions and some monovalent ions. The operational cost is approximately 29% less than reverse osmosis (0.001-0.006 USD/L) [156] and has a high water production capabilities for its weight and volume relative to other membrane technologies [158]. For the higher salinity thresholds in emergencies, partial desalination via nanofiltration may be sufficient for some scenarios and could be an interesting area for future exploration.

2.7.2 Reverse Osmosis

Reverse osmosis (RO) is the most commonly used system and has numerous cases of attempted adaptations to emergency scenarios. Some military equipment (e.g., Reverse Osmosis Water Purification Unit (ROWPU)) has utilized RO for seawater and brackish water desalination, but much of this has high capital costs (approximately 36,000 USD), high operating costs (approximately 16,000 USD every 2000 hours) due to membrane replacement and diesel usage, and requires skilled operators with an average of 4 hours daily maintenance [160–162]. Many of these systems have been infrequently used due to the increased reliance of armies on procured, bottled water, especially in Middle Eastern campaigns where water bottling facilities (often large seawater desalination plants) exist. However, some military RO equipment has been utilized for humanitarian deployments, such as the Canadian Disaster Assistance Response Team (DART) using ROWPUs in Haiti [163] and by the British Army using Stella Meta NBCG units (colloquially within the British Army - Water Purification Unit (WPU)) [164]. Some organizations have explored using deployable RO systems such as Katadyn Spectra Maker models, Aspen 2000DM, Karcher WTC500/700, and other organizations have made containerized systems with some employed in humanitarian scenarios (e.g., Mascara, Yemen Boreal Light, Somaliland RO, Aquasisstance, modified Veolia Aquaforce systems). It is unclear though the length at which these systems are successfully deployed and at what point failure occurs; this would be an interesting area of future investigation. Lastly, RO requires extremely stringent feedwater characteristics and encounters practical issues with fouling and scaling [165–167], which has prevented its broader adoption in emergency scenarios.

2.7.3 Electrodialysis

Electrodialysis (ED) is a membrane based desalination technique that is not pressure driven, but rather is electrically driven by differential charge on passing salt water. This lends itself well to robustness against turbidity, and has been historically used in harsher applications including wastewater treatment [168]. It is also generally more energy efficient than reverse osmosis in some brackish water conditions (<3000 mg/L) - depending on recovery ratio - and especially when the product salinity does not need to be relatively low; as the product salinity target lowers, the energy required to desalinate increases non-linearly [169]. Lowered specific energy and operational flexibility lends ED well to PV applications and can shift reliance on diesel [150]. Additionally, there is potential for electrodialysis to be utilized for specific ion recovery, as well as the potential for the technology to be coupled with on-site chlorination. Electrochlorination via electrolysis of sodium chloride is utilized in numerous remote field hospitals by MSF and UNICEF (one example company is WATA) and could be well suited for coupling with electrodialysis desalination in emergencies [170]. ED is not effective at removing heavy metals and other compounds with little to no ionic charge. Additionally, ED membranes and membrane technology in general must remain saturated and carefully preserved once wet which may prove difficult for redeployment due to increased weight and maintenance considerations.

Intermittent operation of any of these membrane processes could cause an increased rate of fouling. Membranes are not commonly procurable locally in low and middle income countries, and most guidelines strongly recommend not letting them dry. Shipment of wet materials, including membranes causes a significant increase in system weight. Membrane technologies also often need periodic cleaning with acid - another potential consumeable that hinders fully self-sufficient operation.

2.8 A call to action

The growing need for desalination in humanitarian emergencies and in international development is increasingly apparent with cases of saline groundwater and intrusion in areas from coastal flooding to IDP and refugee camps. This need is not well quantified, but is inferred through numerous case studies in literature and from interviews with practitioners, and is most obvious in the Middle East, Southeast Asia, and parts of Africa. Much of these regions correspond with high groundwater salinity and high risk of disaster and/or conflict. While NGO operational standards currently lack guidance on saline water treatment, systems for treatment of salinity and chemicals will become increasingly necessary. Some humanitarian BWT requirements including transport regulations, weight, size, simple operation, minimization of consumables, and reliability in extreme weather conditions are not common design requirements for membrane and thermal desalination technologies and thus have historically hindered their adoption and usefulness in the field. RO variants have been attempted in the field, but often fail due to rapid fouling, a lack of a reliable supply chain for replacement cartridges, and the complexity of system operation. NF has not been attempted as frequently in field desalination usage, but could have greater potential as it trades off desalination capability for operational robustness. ED is another technology not attempted to the authors' knowledge in humanitarian deployments, but has great potential for solar deployment, coupled electrochlorination, and other mineral and resource extraction (e.g., hydrogen production in a protracted scenario). Distillation techniques do not appear to be feasible for large scale BWTs at this time due to their lack of production quantity and high energy requirements, but do boast potential simplicity and composition agnostic treatment.

Future work could include exploring the design of NF and ED systems and redesign of RO for these requirements. Higher target salinities could provide opportunities for these technologies to be implemented with membranes that sacrifice some amount of salt cut for robustness to turbidity and a broader range of feedwater compositions. Exploring reverse osmosis techniques that decrease fouling and clogging such as cross (tangential) flow plate and frame reverse osmosis or exploring the usage of hollow-fibre membranes, rather than commonly used spiral wound polyamide based membranes, would be interesting and could show higher potential for the usage of RO in crises scenarios. NF and ED systems have not been designed for this context; exploring the design of a flexible system that can desalinate a variety of feed salinities and turbidities is another area that should be explored, as traditional desalination systems are commonly designed for a highly specific feedwater composition and a specific target composition. A concentrated chlorine stream in electrodialysis could be extracted and utilized for disinfection of water, providing a substitute for another essential consumable; however, a challenge exists in separating this chlorine from other negatively charged ions in this concentrate stream. Another area of significant potential includes exploring minimal consumable prefiltration techniques; identifying and optimizing the architecture and design of low maintenance alternatives to cartridge filters such as disc, sand, and even hydro-cyclones has not been explored in this space. Thermodynamically and technoeconomically comparing these processes within the context of crises would be highly beneficial. Finally, future work should include investigating more social factors (such as distribution practices, taste thresholds, use profiles) that are context specific; neglecting such factors could severely reduce the effectiveness of a system that is designed only for the initial requirements mentioned in this work. A desalination system designed to meet the needs of humanitarian crises would be a substantial step in adopting desalination technology not only for disaster and crisis response, but also for providing water in other highly-constrained communities.

The subsequent chapters explore the development of electrodialysis as a technology that can be appropriate for these scenarios. Specifically, this work explores the mitigation of battery usage and simplification of control for PV EDR systems. EDR systems have significant potential for usage in harsh feedwater contexts, have long membrane lifetimes (on the order of ten years), are highly energy efficient and can consequently be operated off-grid with compact solar arrays, and have low water wastage. PV-EDR systems are also cost competitive with on-grid reverse osmosis. However, PV-EDR systems have not been explored in the context of humanitarian crises and deployable scenarios: improvements and considerations must be made for the increased weight and volume of EDR systems and in reduction of battery capacity. Reducing or eliminating batteries in PV-EDR for deployable scenarios would be beneficial in eliminating a failure mode, lessening maintenance, simplifying the operational characteristics of the system, facilitating air-shipment, and reducing the capital cost. Accomplishing this is a fundamental step in adopting desalination for highly-constrained scenarios.

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Chapter 3

Theory: Direct-drive electrodialysis desalination

The following are governing concepts for the design of a simple, low-cost, minimal maintenance and minimal battery capacity electrodialysis desalination system which may be subject to power variations over time.

3.1 Governing theory of direct-drive electrodialysis

3.1.1 Electrodialysis desalination behavior

Electrodialysis is an electrically-driven process which has a fundamentally different means to separation than pressure-driven membrane processes such as nanofiltration and reverse osmosis. It is consequently more energy efficient than reverse osmosis for many brackish water desalination conditions [1]. Electrodialysis operation can be continuous (water travels in a single-pass through the system), batch (water travels in multiple passes through the system, see Fig. 3-1), and semi-batch [2].

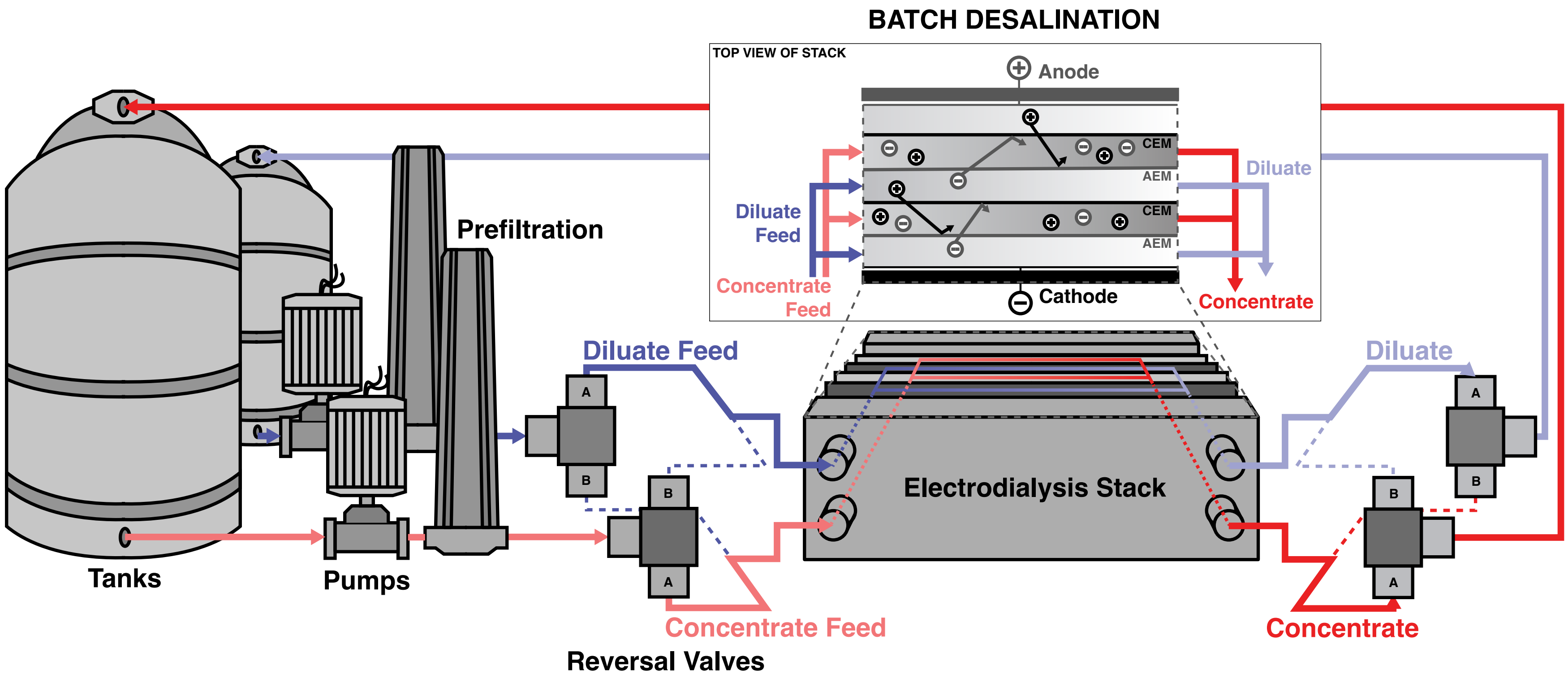

Figure 3-1: Typical architecture for batch electrodialysis reversal desalination

Batch systems can reduce the capital cost because of the reduction in membrane area (which dominates cost) in contrast to a continuous system [2, 3]. Batch systems are also common modes in commercial operation when output water requirements may vary [4]. Prior art exists in maximizing the reliability and minimizing the cost of batch electrodialysis systems using approaches such as flexible operating schedules [5]. Connors demonstrated a weather-predicted energy management system which considers both optimal energy storage and a concurrent optimization of a batch EDR system [6]. Batch and semi-batch systems additionally enable flexibility in input and targeted output conductivity because water is allowed to recirculate indefinitely throughout the system, whereas continuous systems are generally immutable.

For this implementation, we consider batch electrodialysis to minimize capital cost and to incorporate flexibility for variable feed and target salinities which occur in practice over time (e.g., a borehole may experience seasonal fluctuation in salinity). While we consider implementation of batteryless desalination on batch EDR, much of the governing theory translates to other electrodialysis systems (e.g., hybrid-batch and with some aspects applicable to continuous systems; though operational objectives may change).

Direct-drive desalination objective

Traditional systems with energy storage can consider predictive energy allocations (when to charge and discharge energy storage) to accomplish a variety of goals including increasing the energetic efficiency, meeting a target production rate goal, minimizing the cycling of batteries and thus maximizing lifetime, and more. However, direct-drive systems do not have this luxury. These systems rather employ immediate information for immediate decision-making. **The aim of a direct-drive desalination controller should be to maximize the instantaneous water production rate, due to a lack of energy storage (i.e., a battery).** In other words, this strategy utilizes all of the energy available at any given time (hence, direct-drive), and gives the proper allocation of energy to the subsystems that maximizes the desalination rate at that point in time.

3.1.2 Maximizing current and flow leads to the maximum water production rate in a batch system

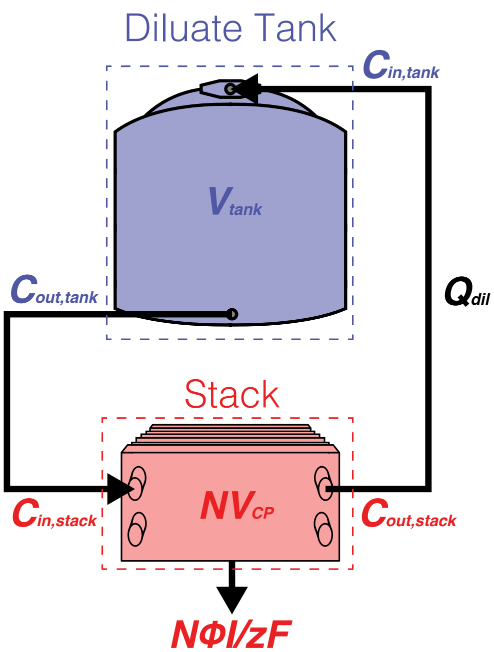

Figure 3-2: Mass balance on diluate tank and electrodialysis stack

Desalination rate is characterized by the following equation derived from a mass balance with respect to the stack (see lower control volume of Fig. 3-2), where the first component describes the change in concentration of the stack over time, the second component describes the influence of flow rate (and can be related to the change in concentration of the tank), and the third describes the mass of charge transferred driven by current. We neglect back diffusion in this description because it has been modeled and experimentally shown to have small and sometimes negligible effects on desalination rate and specific energy consumption, especially for high current densities and flow rates [7]. Though too large of current densities can cause a significant concentration gradient across the membranes and begin to increase back diffusion [8].

$$NV_{CP}\frac{\partial C_{stack}}{\partial t} = Q_{dil}(C_{in,stack} - C_{out,stack}) - \frac{N\phi I}{zF} \tag{3.1}$$

In this equation, N is the number of cell pairs in the electrodialysis stack, V_{CP} is the volume of each cell pair, $\frac{\partial C_{stack}}{\partial t}$ is the instantaneous change in concentration with respect to time (the desalination rate), Q_{dil} is the flow rate of the diluate stream, $C_{in,stack}$ and $C_{out,stack}$ are the concentrations into and out of the stack respectively, ϕ is the current leakage factor, I is the current through the stack, z is the ion charge number, and F is Faraday's constant.

Note that we want $\frac{\partial C_{stack}}{\partial t}$ to be maximally negative. We want $C_{out,stack} < C_{in,stack}$ because we want a decrease in concentration over time in the diluate channels. The two parameters we have active control over are the flow rate and current of the system. Thus, to achieve a maximally negative first term, we must aim to minimize Q_{dil} while maximizing I. This can be intuitively understood as maximizing the flow of ions across membranes in the system (maximizing current) while keeping water within the system for the longest period or residence time (by minimizing flow rate). We can now see, **to maximize the desalination rate within the electrodialysis stack, we must maximize current and minimize the flow rate.** However, the maximum current applicable is non-linearly, positively related to the flow rate; in practice, there is a delicate balance between these two variables which produces the optimal desalination rate within the stack, which is discussed further in the next subsection.

In order to maximize desalination rate of a batch system (not just the stack itself), we must simultaneously balance the maximization of I and $\mathbf{Q_{dil}}$ (rather than minimize it). This can be easily seen when considering a mass balance of the diluate tank (see upper control volume in Fig. 3-2).

$$V_{tank}\frac{\partial C_{tank}}{\partial t} = Q_{dil}(C_{in,tank} - C_{out,tank}) \tag{3.2}$$

Here, V_{tank} is the volume of the diluate tank, $\frac{\partial C_{tank}}{\partial t}$ is the desalination rate of the diluate tank, and $C_{in,tank}$ and $C_{out,tank}$ are the concentrations of water going into and out of the diluate tank, respectively.

Increasing the current on the stack will increase the concentration difference between the inlet and outlet of the stack (by decreasing $C_{out,stack}$), and thus also increase the concentration difference between the inlet and outlet of the tank $C_{in,tank} - C_{out,tank}$. Increasing the flow rate Q_{dil} will increase the rate at which this tank is experiencing desalination as salty water flows quicker out of the tank and fresh water flows quicker into the tank. The same concept is also proven in [9].

3.1.3 Constraints on the applicable amount of current

We aim to maximize current, however, the amount of current we are able to apply is constrained by two important factors: (i) available power and (ii) limiting current.

(i) Available power can be variable, especially with renewable energy sources such as solar or wind.

(ii) Limiting current is the threshold at which water will begin to dissociate and begin to generate acids. It is, colloquially, the point at which water splits. An expanded equation for limiting current density is shown below, adopted from [10].

$$i_{lim} = \frac{\mathbf{C}_d zF}{t^{AEM,CEM} - t_{+,-}} \frac{D_{aq}}{d_h} * \alpha\left(\frac{\rho_{aq}}{\mu} \frac{\mathbf{Q}}{\epsilon whN} d_h\right)^{\beta} \left(\frac{\mu}{\rho_{aq} D_{aq}}\right)^{\gamma} \tag{3.3}$$

The terms $\alpha = 0.29, \beta = 0.5, \gamma = 0.33$ are empirically determined factors which influence the mass transfer coefficient, but have been shown to closely match the performance of many stack sizes and geometries [10]. Limiting current is a dynamic constraint that changes based on the water salinity, C_d and Q. If we are commanding limiting current (with some safety factor), we are maximizing the allowable current and thus desalination rate and water production rate.

We are not necessarily producing the minimum specific energy consumption (SEC). Operating at higher current densities often leads to lower specific energy consumption (we aim to operate at the highest); however, in a direct-drive system, minimizing SEC is not an aim. In a direct-drive system, SEC is not as useful a metric because the objectives of direct-drive systems are to utilize all of the energy available at any given time in the best way possible (due to a lack of energy storage and thus, future decision-making). The best operational strategy is to maximize the water production at any given time with the power available - not necessarily to waste energy and limit the system so that we can operate at a more efficient desalination point, i.e., the minimum SEC.

The consumed and available power, flow rate, concentration, and limiting current are coupled levers and constraints. The coupled behavior can be observed in Figure 3-3.

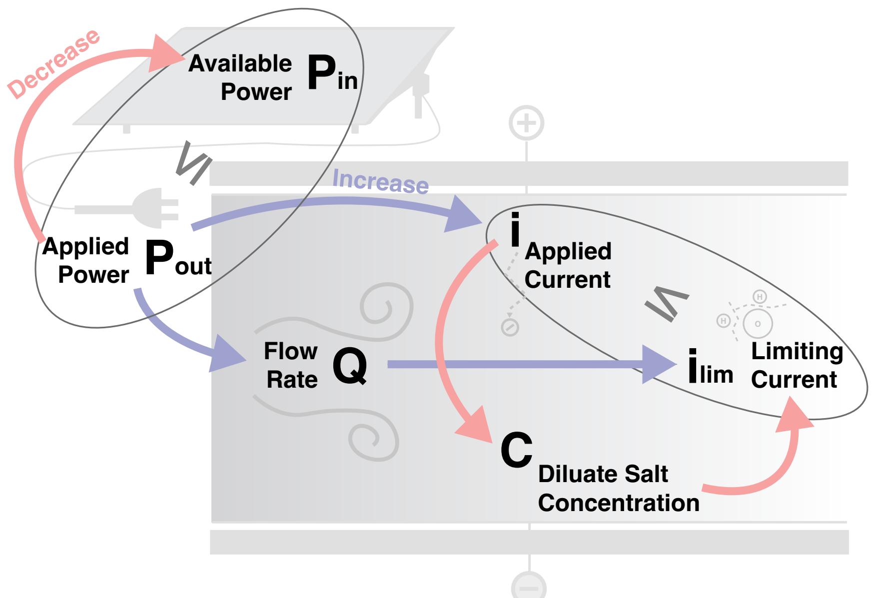

Figure 3-3: Conceptual flowchart of coupled relationships in electrodialysis desalination

The two active levers we have control over are the flow rate and voltage applied to the desalination stack. More generally, we allocate power to the motor(s) which drive the pumps while also allocating power to the desalination stack electrodes. We can see within this conceptual flowchart, that as we increase flow rate, we also increase the limiting current and thus the amount of current we can apply to the system. However, as we increase current, we are increasing our desalination amount per pass through the stack and thus decreasing the salt concentration at the stack outlet. Decreasing this diluate salt concentration at the stack outlet in turn, decreases limiting current. Finally, when we apply increased flow and current, we also decrease the power available. The reader can observe the trade-off between the ideal amount of flow and current to apply is complex and not well characterized.

For a given power, we want to maximize the current density applied to the stack (maximizing our desalination rate) while applying sufficient flow rate to immediately use all of the available power. This strategy produces the maximum water production rate possible for a given amount of energy [9].

3.2 A simple, intuitive, broadly applicable control scheme: Flow commanded current control (FCCC) for electrodialysis

3.2.1 An intuitive primer for how the controller works

We propose a simple, real-time responsive approach which aims to minimize computation time while quickly and consistently producing solutions that maximize water production rate of an electrodialysis desalination system.

We can best understand this scheme by first thinking linearly in steps through each component (Fig. 3-4).

1. If we have some surplus power, we can command some more flow via the motors and pumps. This flow rate will then positively influence limiting current (the maximum desalination limit).

2. We then can apply a current equal to limiting current with some safety factor.

3. The current and flow rate we command together consumes some of our available power.

4. If we continue to ramp up the flow rate, and thus ramp up the current which is positively coupled, we ramp up the power utilized until this matches the available power.

5. If we suddenly are using too much power, we can simply ramp down the flow rate, which decreases the limiting current and concurrently the actual applied current. This holistically decreases the power utilized.

The main idea is that we always apply the maximum allowable current to maximize our desalination rate, while adjusting the flow rate around it to match the available power.

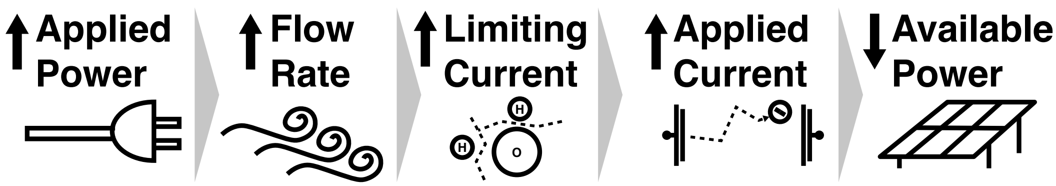

Figure 3-4: Conceptual flowchart of FCCC

To accomplish this concept, our application leverages a cascade control system with (i) an inner current control loop and (ii) an outer flow control loop controlled in our implementation by a PID controller (Fig. 3-5). A cascade controller is a feedback controller that involves a nested loop where the inner control loop is reliant on what occurs in the outer control loop.

3.2.2 Inner loop: maximizing desalination

The inner loop involves current control on the desalination stack. **We dictate that the current commanded to the stack is always some threshold (safety fac-**

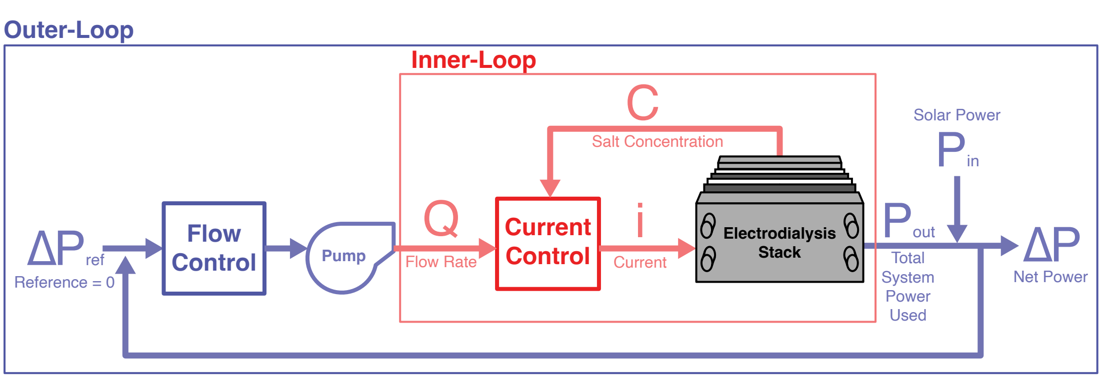

Figure 3-5: Simple block diagram figure of FCCC

tor) of limiting current density.

$$I_{cmd} = \eta(i_{lim}A) \tag{3.4}$$

In this equation, η is a threshold safety factor, i_{lim} is the limiting current density calculated from the diluate concentration and flow rate at the end of the stack, and A is the effective membrane area.

This inner loop calculation only has two dynamic variables. **Thus, this concept relies solely on two sensor measurements: flow rate and diluate outlet conductivity.** All other parameters are static and defined by the desalination stack architecture.

This current controlled approach is advantageous to voltage control, because the power supply will aim to provide the same current regardless of a variety of load conditions. Prior studies that use voltage control must include a model or scheme for calculating the real-time resistance of the stack; under current control, no calculation of the stack resistance is necessary. This is a key reduction in computational load. Prior art which focuses on calculating voltage required to induce limiting current relies on models of stack resistance which can be complex, inaccurate, and may change over time as membranes and other components degrade.

Current control is accomplished by voltage or resistance regulation, which is a common practice in numerous power electronics architectures. For instance, linear-voltage regulators, transistors, operational amplifiers, and more are utilized for current control [11]. Current control has many practical applications including controlling motor torque (as current and torque can be commonly modeled as linearly related in a motor).

Constant current has been utilized for electrodialysis and other chemical processes in the past (as well as constant voltage control). There are some practitioners which have concern for safety of current control. For instance, operators may worry of sudden high voltage conditions if there is an error made in current calculation (e.g., due to an inaccurate sensor). However, many modern power supplies have adjustable over voltage protection and which have enabled quicker, faster current control. This is especially true due to the modernization of switched-mode power supplies.

3.2.3 Outer loop: tracking power

We employ a PID controller where the process variable (to be tracked) is the net power consumed. Where net power is power supplied by solar irradiance subtracted from the power consumed by the motors for pumping, the EDR stack for desalination, and the latent hardware. Latent hardware includes lower power background operations such as the controller, sensors, cooling fans, etc.

We must aim to keep the net power consumed at a set point of zero, and can view variations in solar power as a variable disturbance on the net power, our process variable.

$$P_{solar} - P_{motors} - P_{stack} - P_{latent} = \Delta P_{net} = 0 \tag{3.5}$$

The net power consumed can be tracked in a variety of ways:

1. *Measuring the current* in and out of a small energy buffer on the input supply rails. This could be a small battery for testing this theory, or could be a capacitor in parallel with the solar array. When the capacitor is charging, the system knows it is able to draw more power from the supply rail. When the capacitor is discharging, the system realizes it is drawing too much power from the supply rails. This scheme involves having a current reading set-point of zero on the energy buffer.

2. *Measuring the voltage* of this power bus or rail. This involves holding the capacitor or battery at a nominal voltage set-point (rather than using a net current of zero). The voltage set-point depends on the capacitor bank or battery configuration and nominal operating points. This configuration is also dependent on the power electronics requirements. For instance, the bus voltage must be within a range at which the power converters can operate. Practically, some

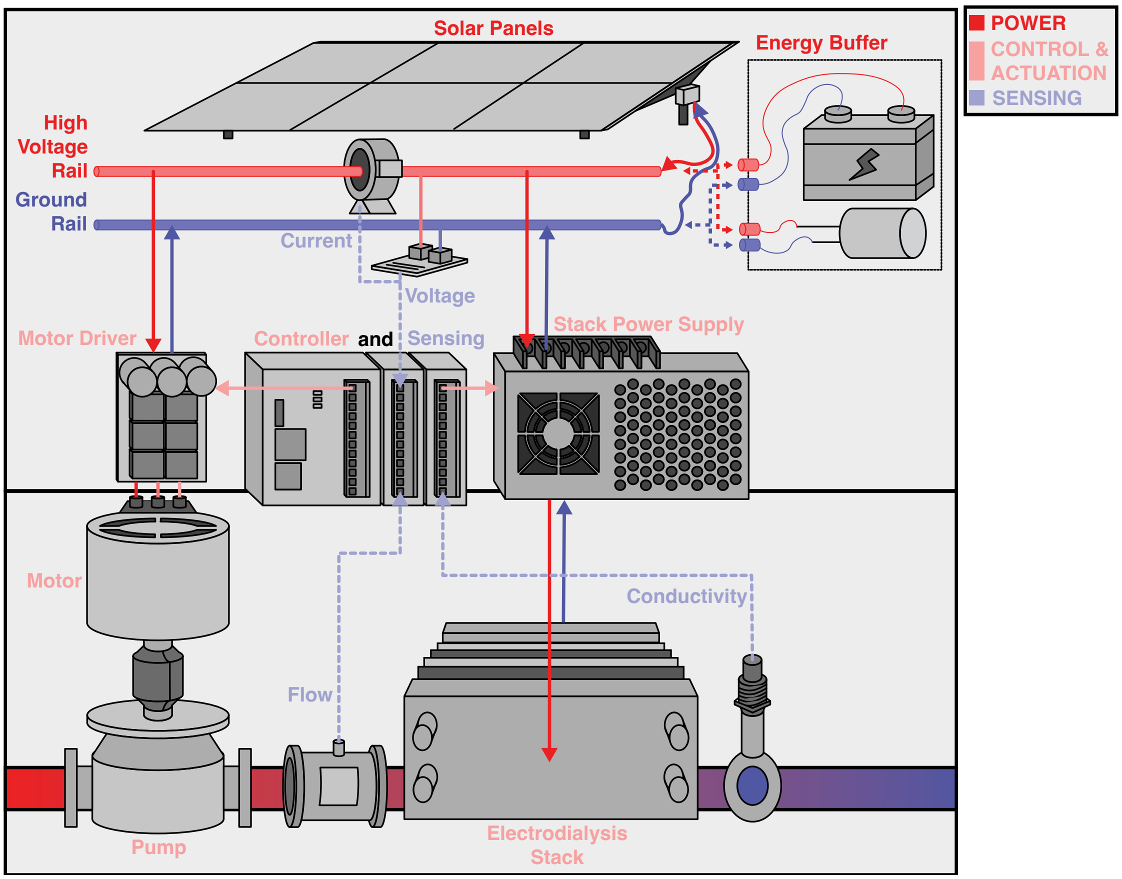

Figure 3-6: Schematic of typical system power and information flows

batteries - such as lithium-ion phosphate - have relatively flat voltage versus percentage of charge curves; these are more difficult to use for voltage tracking because they would require higher sensor resolutions [12–14].

Figure 3-6 shows the two aforementioned sensing methods (voltage and current) for tracking power and where those might be applied in practice. Either a battery or capacitor is shown to be connected to the high voltage and ground rail, and from these rails, power is drawn to subsystems including the pumps and stack. It also shows the control and two sensors for the inner control loop (flow and conductivity).

The output control effort is the motor speed which is connected to a pump, and thus to the flow rate into the stack. Recall, as we increase the flow rate to the stack, the motors and current controller will concurrently draw more power. As we decrease flow rate, the opposite occurs.

This approach is dependent on immediate sensing and responsive adjustment, rather than predictive computation with nested models. It additionally **will readily guarantee solutions and avoids error propagation** that may occur in nested model-based control - especially when the dynamics of the plant may change over time.

Closed-loop feedback control will inherently always produce solutions for flow rate and current. Implemented in the analog domain, this could be on the order of kilohertz or higher. In the digital domain, which is where the system is later implemented and a common realm for control, the rate of solutions produced is limited by the controller sampling frequency.

The current control calculation is fast - it involves one equation with basic algebraic operations. No iterative solvers such as root finding methods or computational loops are required. The reader may think of the PID controller on flow rate as an iterative method for continuously finding the optimal combination of flow rate and current for a given feed salinity and available power. The process variable we track (bus voltage or current) allows us to connect any number of latent power equipment such as controls, fans, etc., and the controller will still be able to readily adapt and operate.

Finally, the outer control loop can be readily translated to track power even in states when we are not desalinating. For instance, when we are filling or draining the tanks to prepare for a batch or are ending a batch, the inner current control loop will be disabled. However, the outer loop can still ramp up and down the pumping speed to fully utilize the available power.

Considerations for cascade control

It is important to note for cascade control to work, the inner loop disturbances must be less severe than the outer loop disturbances. In this case, the outlet conductivity disturbances or changes must be less severe than the disturbances in solar irradiance. This is true, as solar power and net power have variations that are much larger and faster than the changes in conductivity. It is additionally important to note that with nested control loops, the inner loop (current controller) must be sufficiently faster than the outer loop (the flow controller). Typical values are at least three to four times as fast [15, 16].

3.2.4 Controller tuning

The inner-loop control strategy always produces the optimal desalination rate and minimizes specific energy consumption. However, **the practical speed at which power is tracked depends on the outer loop design and tuning**

Tuning PID loops has abundant literature (e.g., [17–20]). This work does not employ any new strategies for PID control or tuning; consequently, the flexibility within the outer loop controller in this proposed scheme may allow for greater adoption in practice. Any number of canonical tuning methods can be applied. However, it is important in any scheme to consider a few factors.

- Firstly, the controller block which tracks power can be substituted with many different methods for linear control (proportional, PI, PD, PID) or nonlinear control (on/off). This work considers PID control with the aim of maximizing the response speed while minimizing overshoot; the PID loop should not cause significant overshoot of allocated power over available power because this will cause significant current and energy from the buffer (battery, capacitor).

- Secondly, there is no one set of tuning parameters that are "perfect" in a PID system, only parameters that meet a designer's desired behavior or requirements.

- Third, how one tunes the PID will affect the speed of the entire system response, and thus will in turn effect the required size of the energy buffer (later seen in Fig. 3-8.)

For any control systems, there are intertwined relationships between sensing speed and resolution, controller sampling frequency (especially relevant in discrete design [21]), actuator capabilities and speed (i.e., How fast can these motors be moved and what is the maximum speed we can apply? How fast can we change current on the stack and what is the maximum current we can apply?). The most ideal control system would have the most accurate, highest resolution, and highest speed sensors. It would have a infinitely fast controller calculations and would have immediate actuator response with unlimited capability (e.g., an imaginary motor that could spin up to a very fast speed withstanding any amount of torque instantly). With real hardware, this is certainly not the case, and practical limitations on speed, resolution, and capability (control effort) will limit the power tracking and dynamics of the system.

In our application, we utilize PID control, which consists of three parameters to be tuned:

1. Proportional Gain - in our application, the weight of how much the net power differential affects our new pump speed.

2. Integral Gain - takes into account the time at which we have some error in power tracking and gains more and more influence over time.

3. Derivative Gain - this considers how quickly the error in our power mismatch is changing. Increasing this will tend to decrease any overshoots and create more

stability; it can be thought of as a damper. However, it causes the system to be sensitive to noise and respond slower than desired.

3.3 The trade-offs between control speed, actuation, and energetic buffer sizing for a direct-drive system

3.3.1 Understanding the trade-offs using a simple, first-order system model

Depending on practical hardware limitations as discussed earlier, (e.g., the speed of a flow rate response from the motors and pumps, the resolution of the current or voltage sensor) a small power buffer may be necessary with this strategy. In Fig. 3-7, if more power is utilized by the system than available from the power source such as a solar array, an overdraw is observed and energy must be pulled from the energy storage device. If less power is utilized by the system than given from the solar array, this extra power is directed towards charging capacitors or batteries.

Common power electronics hardware often has some built in capacitance and energy storage. For instance, utilizing a larger solar array has some greater inherent capacitance lending it to less severe voltage fluctuations. Similarly, a larger motor driver will often have some more inherent capacitance to handle spikes in demand relative to a smaller driver.

Having faster control sampling rate (the rate at which we are able to observe the process variable) and actuation creates faster response to power fluctuations in a direct-drive system, and thus allows smaller and smaller energy storage devices to compensate for delays in response (see trade-offs box in Fig. 3-8; as our pump size and controller speed and resolution are increased, the required battery decreases in size). Hence, for a given control speed and magnitude of capable control effort influenced by hardware limitations, we may explore the sizing requirement of this energy buffer.

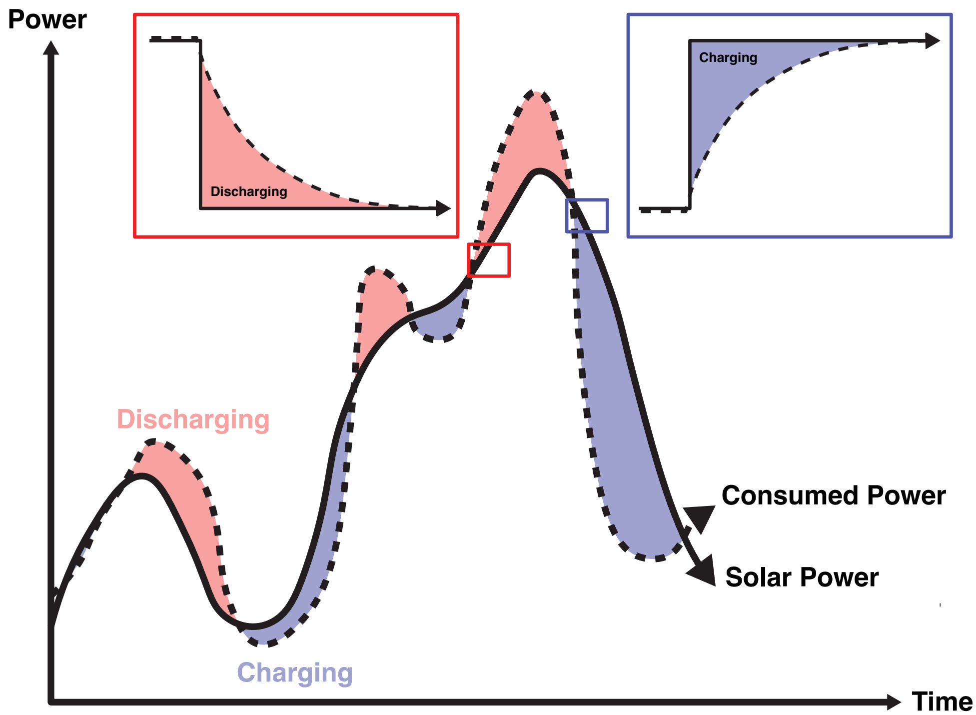

Figure 3-7: Power tracking behavior for a direct-drive system

A simple method for this desalination system uses a first order model of the power response, which is inherently derived from hydraulic transients - the slowest aspect of the plant - for PID tuning and energy buffer sizing.

This system which we are controlling is the plant, which when incorporated with our controller model can later incorporate solar irradiance profiles as input disturbances to predict behavior in practice. A first order plant model has some characteristic exponential growth or decay towards a final value, and is akin to the power dynamics observed from electrodialysis desalination.

Consider a step response of the system in a worst-case-scenario disturbance, as shown in Fig. 3-8. This initial point occurs when the system is fully saturated with irradiance and can fully command its actuators to their maximum capabilities (i.e., if there was an infinitely large power source and all levers were turned all the way up - this is the maximum control effort). The response behavior is what would be experienced if the system was shifted immediately to zero irradiance, and thus, zero available power (metaphorically similar to throwing a blanket over the solar panels when they were just at the sunniest part of the day). This response behavior is influenced by the maximum the actuators can output (max. control effort), and by how quickly the controller can respond (control speed). **This is the worst-case-scenario for the system, and the response from this scenario can aid in determining a safe approximation for the energy buffering required.**

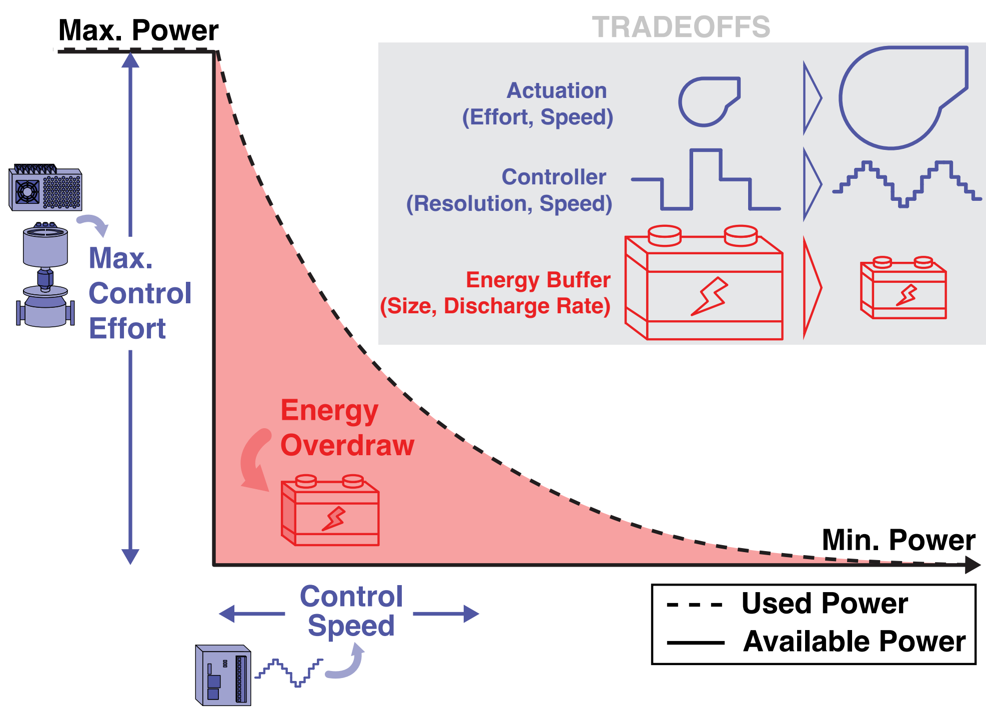

Figure 3-8: Worst-case-scenario step-down in power and the associated energy overdraw assuming a first order response with conceptual trade-offs between actuation, control, and energetics.

Note, how we tune the PID (or other control schemes) influences this control speed and thus, how well the control scheme responds to this power disturbance. A PID scheme that is tuned for rapid response may have large proportional gain and little derivative gain, leading it to a quick response and control speed - however, this quick response could cause overshoot in cases when solar power is increasing; the system may think it has more power than is available, and over-corrects by using too much power. Contrarily, increasing derivative gain could cause the system to respond too slowly to changes, even though it is more stable. There is a balance in which these parameters must be designed, and the final design of these parameters influences the control speed, and thus the energetic buffer required for operation.

3.3.2 Quantifying maximum power draw and response speed to determine energy buffer sizing

In Fig. 3-8 the response has two design factors, (i) the maximum control effort and (ii) the control speed, which can be parameterized to determine the (iii) minimum viable energy storage requirement.

The equations below describe a simple first-order system model for power and the calculation of energy.

$$P(t)_{step,down} = Ae^{-t/\tau} \tag{3.6}$$

$$P(t)_{step,up} = A(1 - e^{-t/\tau}) \tag{3.7}$$

$$E = \int_0^\infty P(t)dt \tag{3.8}$$

Where A describes the initial and final state of the system, which is the maximum power draw the system is capable of producing. τ describes the time constant of the system response and can be related to the actuator speeds, control speed and tuning. E is the energy required by the energy storage device to compensate for this overdraw.

(i) We can quantify the maximum power draw (maximum control effort) based on the system hardware. This can be done via an analytical model by summating the maximum operating power from hardware specifications or other models for power of all system components when actuated to their maximum capability. This can also be accomplished via observation or experimentation by simply commanding 100% control effort from the control loop and observing the power consumed. This is more accurate to reality, but is disadvantageous in that it is designed a posteriori.

(ii) We can determine a final response speed by understanding the coupled behavior of the controller tuning and speed with the intrinsic plant speed. With an analytical model, using the motor capabilities and pump inertia, we can estimate the plant time constant. This plant and a tuned controller can be holistically modeled to estimate the final system response speed. The final response speed can also be found again, by using observations or experimentation. 100% control effort can be commanded and the plant time constant can be observed.

(iii) Once the maximum power draw and final response speed are modeled or empirically determined, we may integrate the system response to determine the energy overdraw, E, and thus the buffer needed to accommodate this system design.

However, regardless of plant and controller dynamics, the fastest controllable speed is dictated by the sampling frequency; a process can only be controlled at a speed that is less than or equal to half of the speed at which the process variable is sensed [22, 23].

This energy overdraw, E, can be used as a design requirement for a capacitor bank or battery. Once the energetic requirement is understood, and the current spikes and nominal operating voltages are understood, then the approaches to sizing the energy buffer are well documented in literature [24–26].

In the case of a capacitor (or capacitor bank), some basic canonical steps are as follows.

1. Determine the worst-case-scenario energetic overdraw, E.

2. Determine the nominal operating voltage V_{nom} and minimum viable voltage V_{min} of the capacitor(s). This will vary based on the hardware requirements.

3. Solve for the capacitance required using $C = 2\Delta E_c/(V_{nom}^2 - V_{min}^2)$.

4. Consider the current spikes the system might experience for this worst-case-scenario power spike knowing the nominal operating voltage.

5. Incorporate the capacitance, operating voltage range, surge current and potentially the inrush current to determine the proper capacitor(s).

In the case of a battery, some basic canonical steps are as follows.

1. Again, determining the worst-case-scenario energetic overdraw, E will determine the minimum energy capacity of the battery.

2. The battery voltage will be sized from the power electronic requirements. For instance, a power supply or converter which intakes 48-60V will require the battery to be nominally between this range.

3. Again, consider the current spikes the system may experience at the nominal battery voltage and ensure the battery is capable of this discharge current.

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Chapter 4

Proof of concept: initial field testing of FCCC PV-EDR

This control theory presented in the preceding chapter was tested for proof of concept on a community-scale electrodialysis system with the aim of (1) determining if the controller concept is stable in practice to variations in solar irradiance and to disturbances within the inner control loop, (2) to see its solar tracking performance against heuristic tuning of PID parameters (similar to what an operator in a low-resource setting may do), and (3) determine the minimum energy storage requirement on this system after empirically observing data.

Note, this chapter does not follow the ideal theoretical methodology as alluded to in prior sections. Ideally, there would be (i) initial system identification and modeling, then (ii) controller design and tuning, (iii) simulation, and then (iv) comparison of results to these simulations. Instead, to save cost on initially validating this concept, we implemented this scheme on a modified test bed (Fig. 4-1) from previous work by Grace Connors and Simone Gelmini [1]. Due to system hardware constraints and time constraints, the aforementioned methodology was not followed - rather, (ii) was accomplished heuristically and (iv) did not have comparison of results to simulations. However, these initial results do provide a proof of controller concept and show promise for future work.

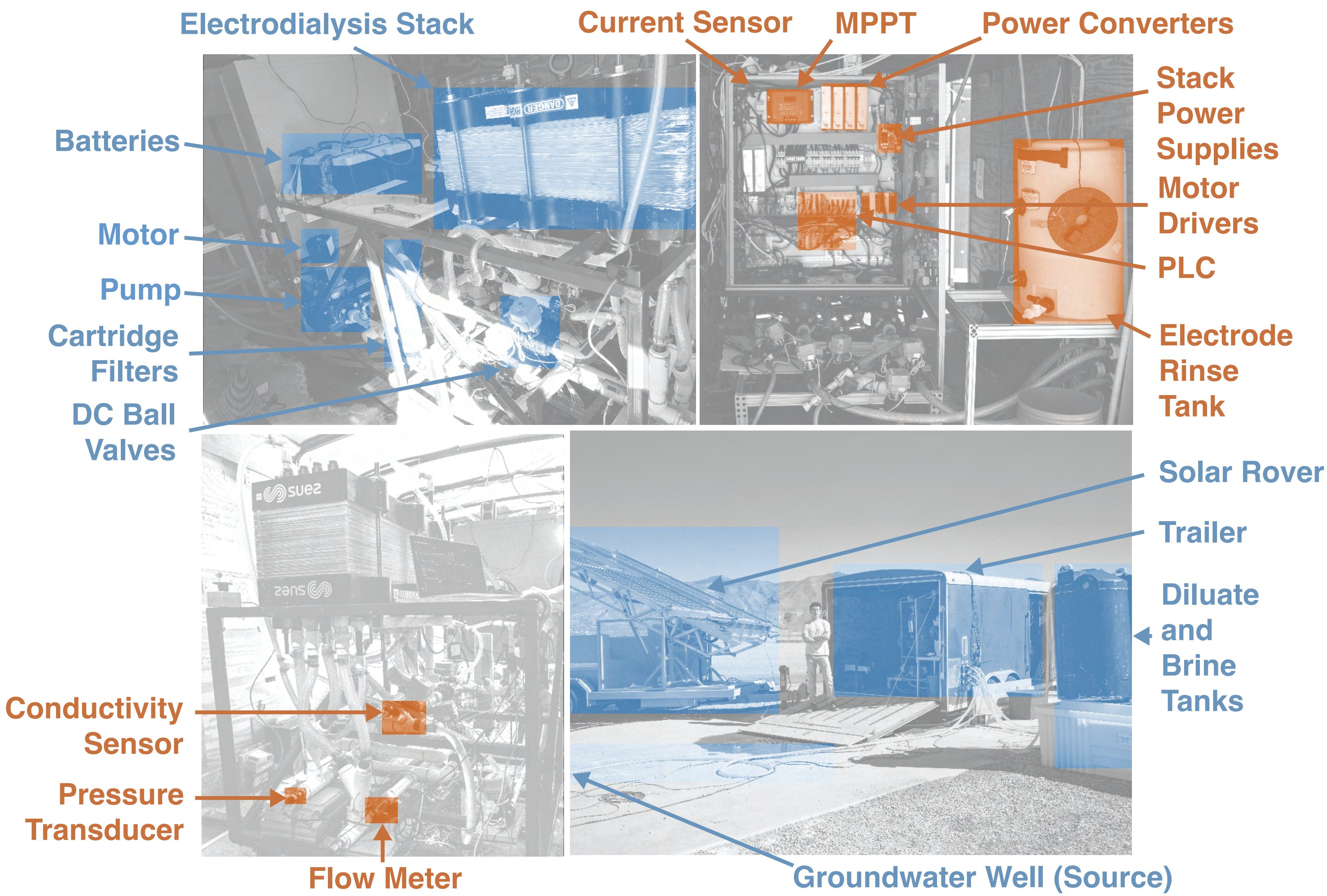

Figure 4-1: Modified Experimental Test Bed Setup

4.1 Hardware

The key components the modified test bed consisted of:

- Hydraulics
  - SUEZ V20 prototype electrodialysis stack (2021)
  - 85 gallon diluate tank
  - 60 gallon concentrate tank
  - 15 gallon electrode rinse tank
  - 100 cell pairs
  - 1 1/4 inch PVC (nominally)
  - 1 inch reinforced hoses
- Control and Sensing
  - Koyo Click PLCs
  - 3 x ProSense Inductive Flow Meters (1 x FMM50-1001, 2 x FMM100-1002)
  - 8 x ProSense Pressure Transducers SPT25-20-0100A
  - 4 x Omega Conductivity Sensors (CDCE90000 Series)
  - 5 x Split Core Hall Effect DC Current Sensor CYHCT-C3TC
  - Bus Voltage Transducer
  - Victron SmartSolar MPPT
  - 2 x Renogy 48-Volt 50 Ah Smart Lithium Iron Phosphate Battery (2400 wh each)
  - 3 x DeWalt FLEXVOLT 20-Volt/60-Volt MAX Lithium-Ion 6.0Ah (120 wh each)
- Actuation
  - 2 x BLDC motors (NEMA 24 60MM Brushless DC Motor)

  - 2 x BLDC drivers (EM-366 Brushless DC-Motor Driver 12-48V 30/25A)
  - 2 x Centrifugal pumps
  - 2 kW Stack Power Supply (100V, 20A) consisting of (2 x DPS5020 buck converters in series with 4 x 500W Single Output DC-DC Converter Meanwell SD-500 for galvanic isolation)
  - 20 x Motorized DC Ball Valves (Tonhe A150-T32-P2-B)
- Operation
  - 300 L batch size
  - hydraulic channel and electric polarity reversal triggered after 8000 Coulombs of charge saturation on capacitive carbon electrodes
  - 6 panel solar array (1800 watt)

4.2 Software

The controller was implemented using a Koyo Click Programmable Logic Controller which featured a built-in PID graphical user interface. The PLC handles real-time processing and timing, is able to manage the full desalination state machine, and includes the model-based inner current control loop through simple multiplication and division blocks. Data are communicated between the PLC and the sensors and actuators over 4-20 mA, 0-10V, RS232, RS485, and modbus TCP communication. Modbus TCP to MQTT is also utilized for time-stamped monitoring in InfluxDB and Node-RED data handling and dashboard interfaces.

4.2.1 State Machine

A state machine was constructed for this testing with the aid of staff engineers Jeffrey Costello, Shane Pratt, and Elizabeth Brownell. The states are arranged in order of operation and occur with dependency on the prior state. For instance, state 2 cannot be entered without first entering state 1. State 1 leads to state 2, which leads to state 3, and so on until the final state which leads back to state 1. There are some exceptions, where error flags may be raised in case of a failure or safety hazard and the system may transition into a standby state from any of the aforementioned states. Additionally, there is an idle/standby state and low power state which does not follow this chronological dependency logic.

This state machine consisted of the following states.

- Idle/Standby - power off to the system, controls on but state machine deactivated.
- Error state - a state which trips the circuit breakers and disables power to all actuators. Can occur in instances such as overflows, under-filling, over-current or over-voltage, insufficient flow, and more.
- Low Power - power is too low to run the system, but will automatically startup when sufficient power is reached.

1. Fill both tanks - both pumps are commanded and track power via PID to fill both diluate and brine tanks.
2. Fill diluate tank - the brine tank is less volume than the diluate tank for recovery greater than 50%. Consequently, the diluate tank must now be filled on its own, also via PID.
3. Even startup - a practical aspect, triggers the proper valve configuration and electrical polarity in preparation for batch operation and waits a small amount of time to confirm these tasks are done before beginning desalination.
4. Odd startup - the same as even startup, but with the reversal valve configuration.
5. Even desalinate - the FCCC control scheme is now operating, with the inner current control loop commanding current to the desalination stack and the outer PID loop tracking solar power.

6. Odd desalinate - the same as even desalinate, but with the reversal valve configuration.

7. Drain both tanks - after the target conductivity is reached in the diluate tank, both tanks are emptied to their proper outlets: product tank and drain.

8. Drain diluate tank - the diluate tank will often take longer to drain than the concentrate because it has more volume.

4.2.2 PID Tuning

The system in practice was heuristically tuned, initially using the classic Ziegler-Nichols method [2], but eventually was adjusted by feel by the operators and the derivative term was removed (the noise propagation of the derivative term made it track worse in practice; if stability is needed, perhaps a lead compensator rather than derivative term could be explored in future work). The process variable in the feedback loop was current into and out of a large battery pack. The control effort is applied to both of the motors as a percent of total power (0-100). Recall, the motors drive the pumps, flow rate, and eventually influence current to the stack and overall system power consumption. The integral included antiwindup limited by the control effort capabilities: (0-100%) of total motor power.

The tuning parameters used were relatively simple:

- Proportional Gain = 10

- Integral Gain = 1

- Derivative Gain = 0

We initially included a large battery pack (4800 watt hours) to test the solar tracking over the period of an entire day at the Brackish Groundwater National Research Laboratory in Alamogordo, New Mexico. Then after analyzing the data, sized and proved the system functionality on a significantly smaller pack (120 watt hours).

4.3 Results

4.3.1 Large Battery

Solar Irradiance

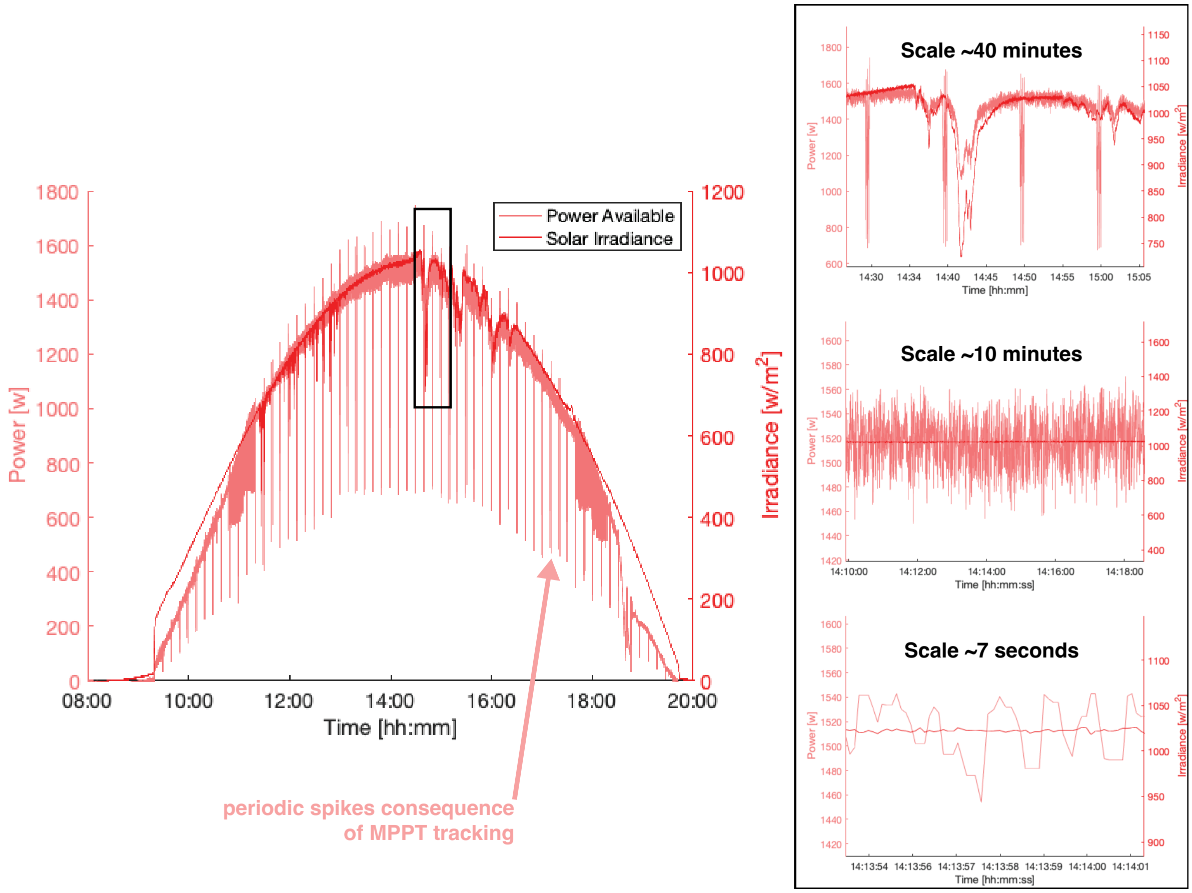

Figure 4-2: Solar irradiance and power throughout a single day of operation

The solar irradiance for this testing day in New Mexico had little variation in solar irradiance with the exception of periodic clouds in the middle and later portion of the day (Fig. 4-2). Note that the jumps in solar irradiance and power available at the beginning and end of the day are due to the solar array being covered by shadows of the trailer which held our desalination system. The curve is consequently not perfectly representative of the solar irradiance and potential power of a perfectly angled, unshadowed system, but shows some of the practical implications to be aware of.

Power tracking and battery charge/discharge

The used power in Fig. 4-3 would have ideally perfectly tracked the available power. However, in practice, there was some overshoot and also some under-drawing of power. This is practically due to (i) a practical sampling rate of approximately 100 ms (the fastest the PLC can handle), (ii) practical limits on hardware actuation capabilities. These include limits on the actuation speed of the power supply and limitations on how rapidly we may change the pump speeds. The single day utilization rate for this particular case was 79% utilization (i.e., 79% of the total possible energy was utilized).

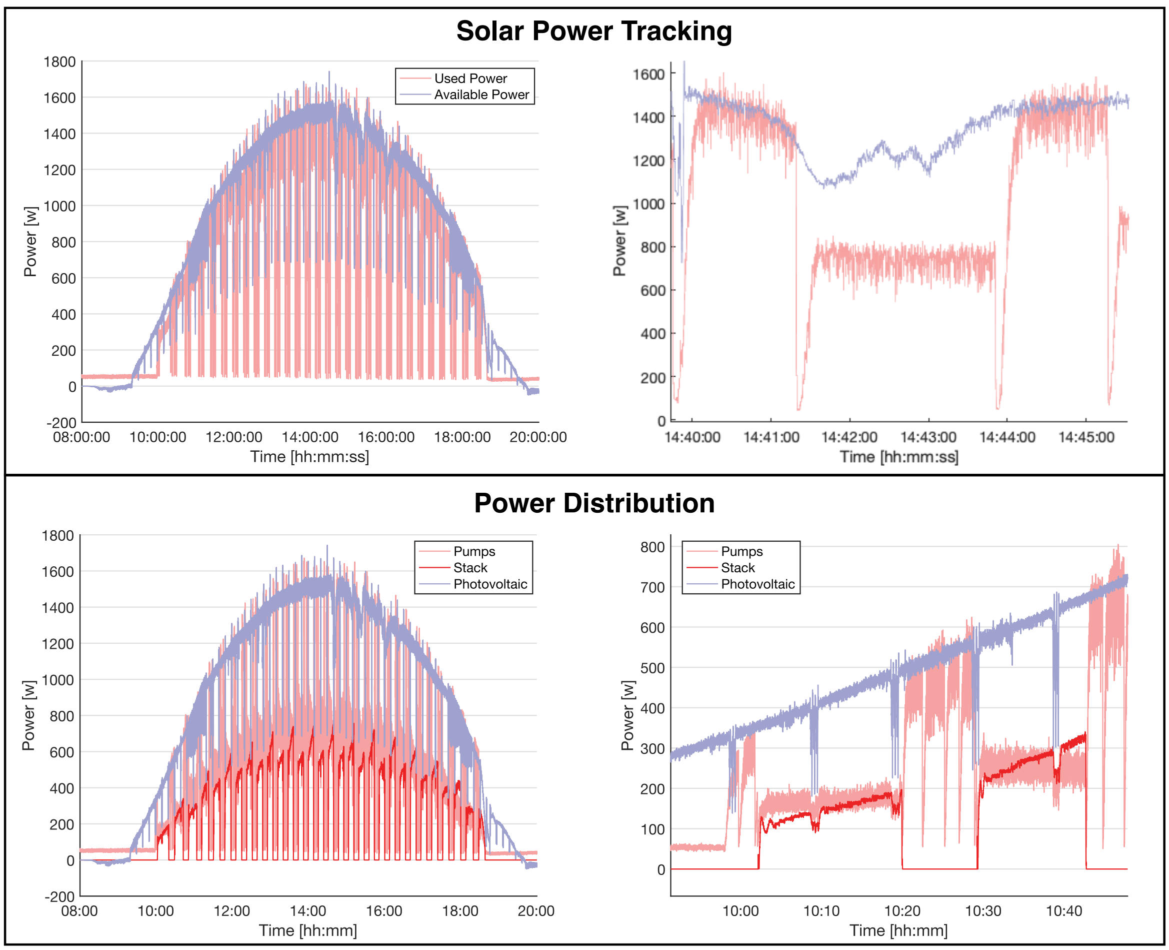

Figure 4-3: Power distribution throughout a single day of operation

Similarly, in an ideal case, battery charge and discharge would ideally be zero watts. The plots in Fig. 4-4 would have no charging or discharging. A battery which did not charge or discharge, would indicate a system load that exactly tracked the solar power available. This would mean there was no excess solar power (which would result in battery charging) and no overdrawn solar power due to excess system power usage (which would result in battery discharge).

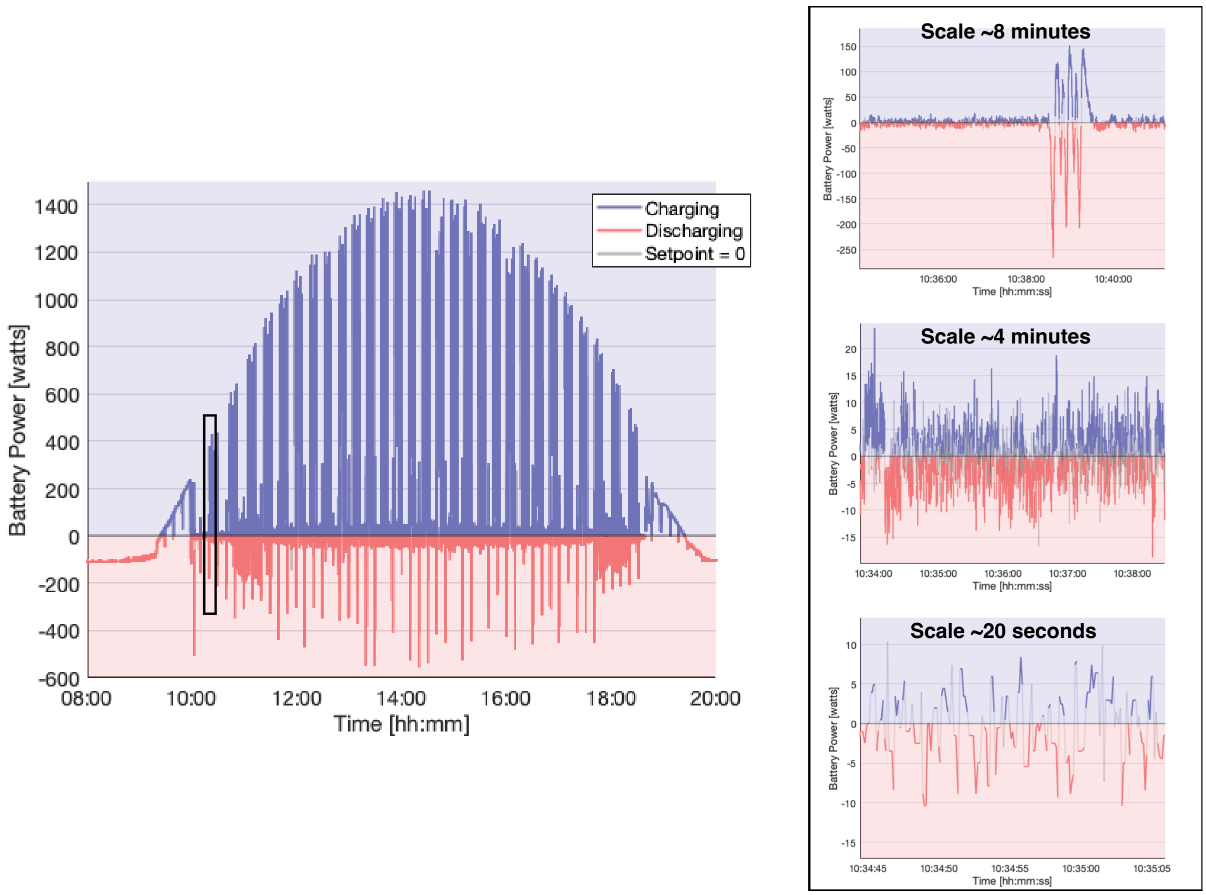

Figure 4-4: Battery charge/discharge throughout a single day of operation

In practice, we observed spikes of charging and discharging and in under-using or over-using power. The battery charging curve in particular followed the solar irradiance curve. However, the largest charging (and under-utilization) spikes are not during desalination. Rather, they occurred during states in which the system drained and filled the tanks. During these fill/drain states, there was excess power, especially in the middle of the day, that went to charging the battery because the motors alone were not able to consume enough power at their maximum to track all of the solar power available. When the stack was consuming power, this tracking occurs much more closely, as seen in some of the scaled figures in Fig. 4-4. Large discharging spikes were sometimes due to state changes, where sudden spikes or changes in load may occur. Properly smoothing the power transitions between these states could be an interesting subject of future investigation. In general, the state of charge of the battery increased throughout the day and the control scheme with the state machine conservatively drew power.

We can also observe the response of the flow rate to the control effort, or the percentage of power the brushless direct-current motors received. Here, we can readily see the time delay in flow rate response - however, it should be noted that it is not this time delay that defines the speed of the control system. Rather, it is how quickly power responds to the control effort.

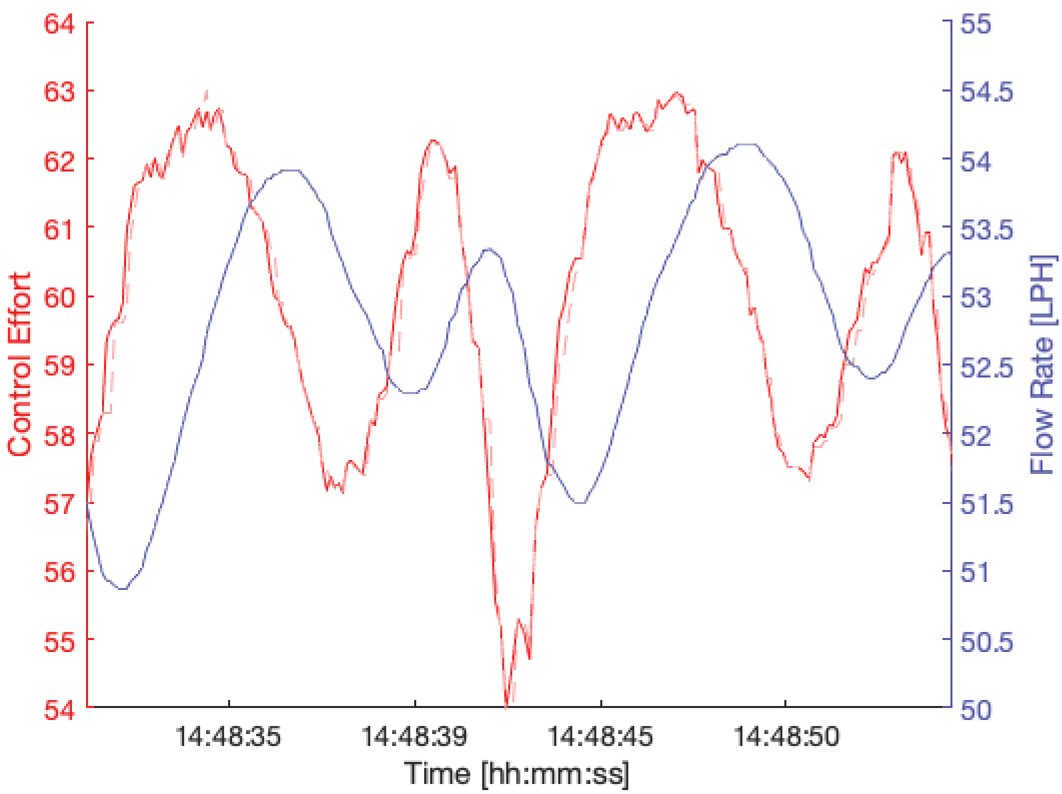

Figure 4-5: Control effort instances during tracking throughout a single day of operation

4.3.2 Small Battery

The battery charge and discharge information was analyzed to determine the largest energy loss and largest current spikes, and we estimated that a 100 wh battery capable of producing approximately +/- 10 amps of surge would suffice for this particular case study. We implemented three DeWalt FLEXVOLT 20-Volt/60-Volt MAX Lithium-Ion 6.0Ah batteries in parallel to handle any large current spikes. This totaled 360 watt hours of battery capacity and was a large factor of safety above our initial estimates.

The small batteries were run for half a day, and then disconnected and we **ran the system off of only one small drill battery (120 watt hours)** for half of the day (we were not able to run for the full day or multiple days due to time limitations at the testing facility, however, this is an aim in future work).

Results from the single battery operation are shown in the following figures.

Solar Irradiance

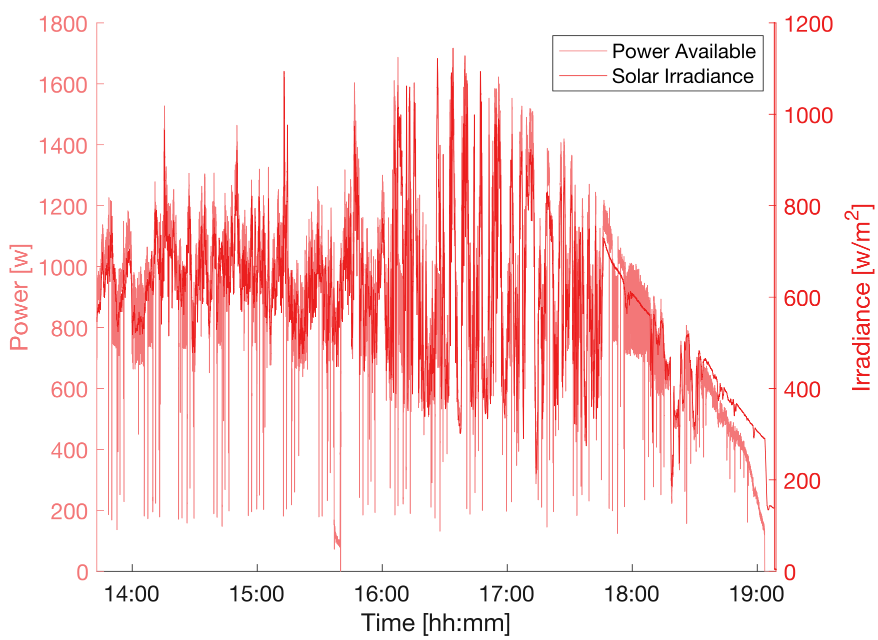

Figure 4-6: Solar irradiance and power throughout a single day of operation

The solar irradiance profile for the small batteries was taken and compared to power over the second half of a day of operation in New Mexico. This day had much more fluctuation in energetics than the day of operation with the large batteries (Fig. 4-6).

Power tracking and battery charge/discharge

Interestingly, **the results from this half-day showed 91.09% accuracy in power tracking** - in other words, we were able to utilize 91% of the available solar power (Fig. 4-7).

We can still see the battery charge and discharge profile follows the available solar power curves, mainly again due to stages of the state machine that are not capable of fully utilizing all of the power (the drain and fill states).

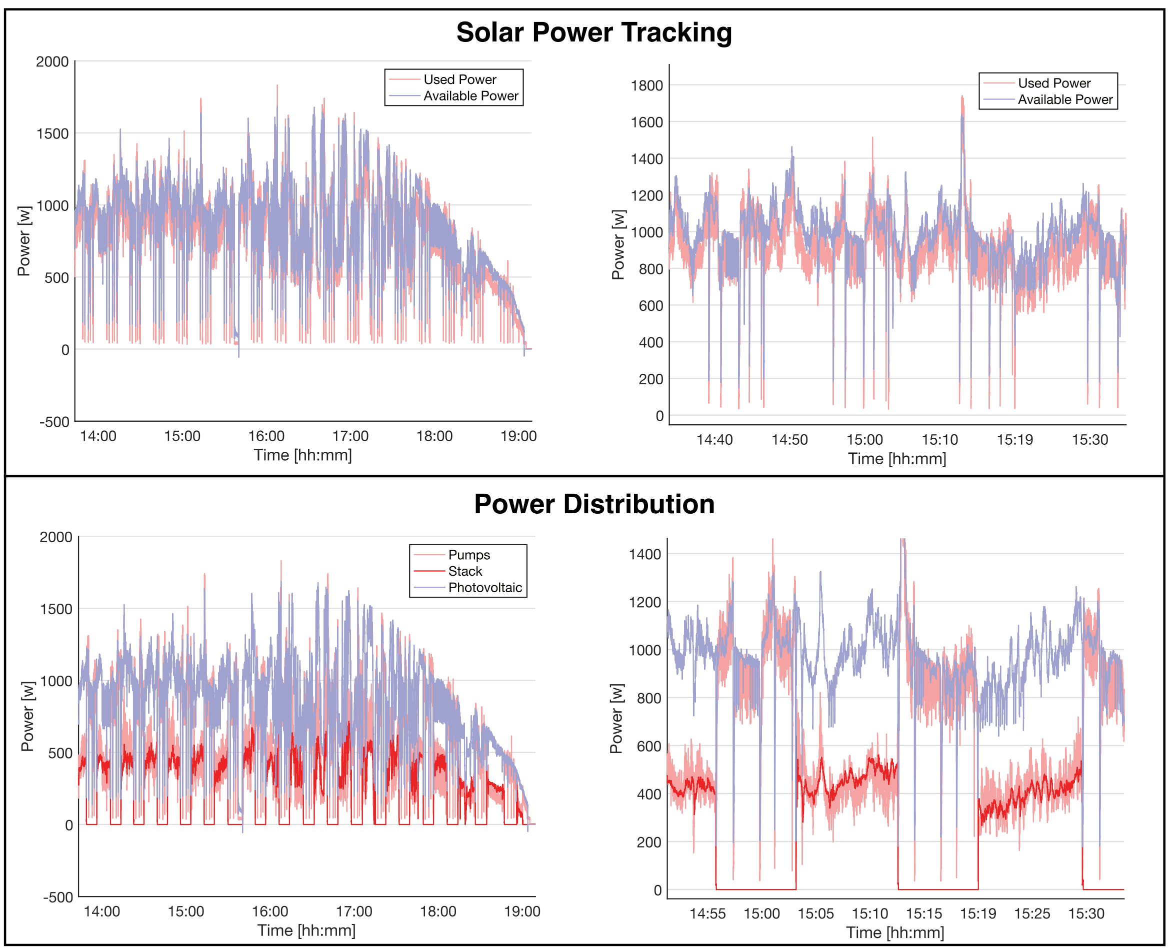

Figure 4-7: Power distribution throughout a single day of operation

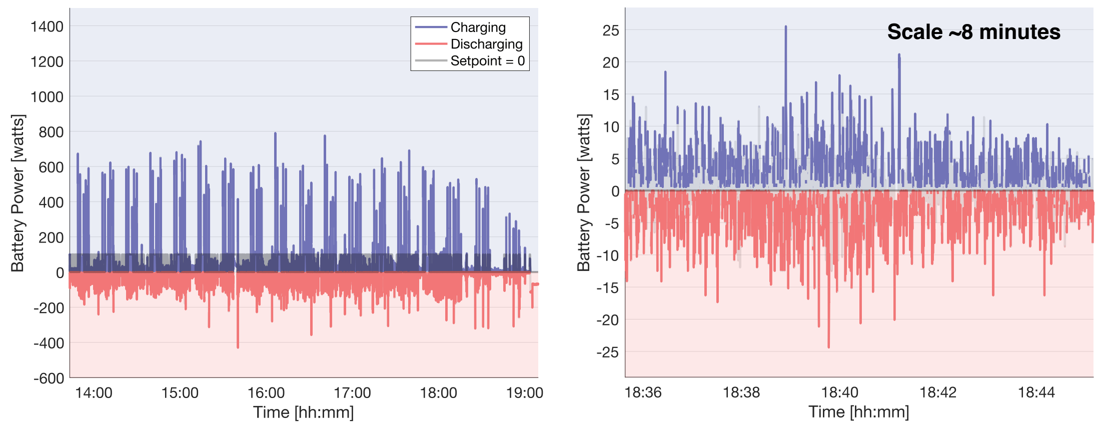

Figure 4-8: Battery charge/discharge throughout a single day of operation

We can see the evolution of practical battery capacity from the system Le Hénaff and He designed in 2019, to recent testing in February 2022 of similarly sized systems in Fig. 4-9. Note some of these prior systems investigated optimal energy storage capacities and operation to reduce the long-term levelized cost of water (though larger batteries increase capital cost), and therefore did not have the overarching objective of complete direct drive operation.

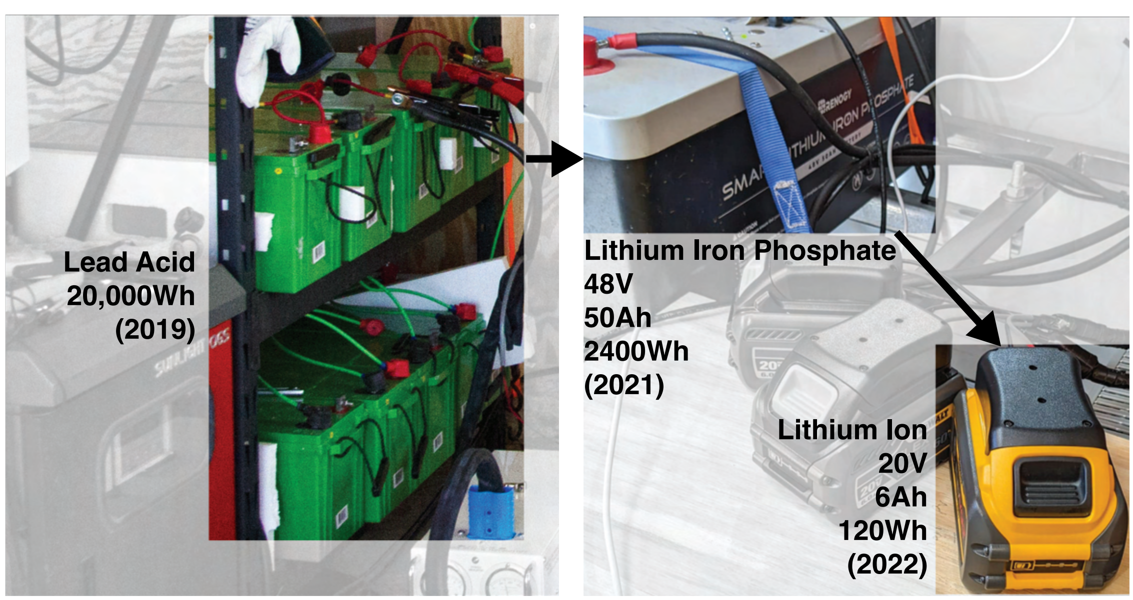

Figure 4-9: The evolution of battery capacity for batch EDR systems in the GEAR lab.

4.4 Discussion

These initial results show great significance in creating a desalination system that is well-suited to humanitarian response and usage in highly-constrained, remote communities. Reducing the battery requirements of the system enables it to be capable of rapid deployment (airshipment), creates simplicity, reduces maintenance, and reduces capital cost. All of these characteristics are important design features outlined in Chapter 2.

Significance to practitioners

The proposed control scheme functioned and was able to reduce the battery capacity by 99.4% while maintaining solar utilization rates of 79% and 91% on two separate days. This solar utilization rate is comparable or better than the optimal control scheme formulated by [3] and is features simple and practically implementable control methods. This reduction in battery size is fundamental for rapid airshipment of a desalination system. Additionally, the reduction in battery size can greatly reduce the capital cost of the PV-EDR system, making it even more cost competitive with on-grid or diesel RO systems. Finally, the reduction in batteries is linked to a reduction in system maintenance and modes for replacement. Minimizing maintenance is one of the key requirements of a desalination system for highly-constrained environments.

The control scheme allows flexibility to variations in hotel loads (additional loads that the system may carry), fast, implemented on real-time control hardware (PLC), and computationally inexpensive. This significant reduction in computational complexity is highly useful to practitioners who want something "as simple as pushing a button," for operation and troubleshooting. It reduces the amount of sensors needed within the system, which is an advantage for reducing cost and failure modes.

Significance to the academic community

The proposed control scheme provides a novel approach to the control of electrodialysis reversal. Specifically, it considers the changes in feasible objectives when in direct-drive operation and proposes a control scheme that optimally meets these objectives (by producing the maximum desalination rate). It additionally proposes a time-variant current controlled approach rather than previous work in constant voltage, constant current, and time-variant voltage control and discusses the benefits and drawbacks of this operation mode. Time-variant current control could be considered in other batch EDR contexts outside of direct-drive operation and perhaps even in some continuous EDR explorations.

Furthermore, this work integrates the practical tradeoffs in system hardware choices and the choice of control scheme on energy buffer sizing in direct-drive operation. It lays the groundwork for sizing actuators (pumps, motors, stack power supplies), for choosing sampling rates (based on the sensor speeds, actuator speeds, controller processing times), and a lower-bound sizing of batteries and/or capacitors in a direct-drive system; such a scheme could be applied to other direct-drive systems even outside EDR and outside desalination.

Future work

While there is significant promise, there are many more routes to be explored. One aspect of importance for a deployable system is the optimization of the weight and volume of direct-drive EDR system - meeting weight and volume specifications are essential requirements for transportation.

Another area that should be explored is the cost and performance tradeoffs when sizing actuators, control speeds, and energy buffers. The sizing of these are all intertwined, but also are intertwined with the practical sizing of the electrodialysis stack and solar array. Considering power electronics constraints and relationships may be an interesting approach for minimizing electronics cost while maintaining practical implementation aspects.

The minimization of consumables and maintenance associated with pretreatment is a third area that should be thoroughly investigated. Such considerations are especially important in remote deployment scenarios where there is a lack of robust supply chain. Cartridge filters are the de facto standard in desalination systems but are not suitable for scenarios which require little to no consumables. A thermodynamic and technoeconomic exploration of pretreatment architectures has not been explored within the context of desalination and humanitarian crises - often systems are sized and built heuristically.

Additional considerations of reliability and redundancy within the EDR system should be explored. Proposed methods include failure mode and effects analysis as well as through long-term testing and field deployments. There are many factors in these scenarios that cannot be anticipated such as usage and consumption profiles, cultural acceptability, etc. Testing in remote and highly-constrained communities would bolster the validation and commercial readiness of a deployable, direct-drive PV-EDR system.

Finally, future work should be conducted on system identification and simulation strategies. The plant (the electrodialysis stack) has been historically modeled in a variety of ways; exploring simple empirical or parametric system identification approaches and their performance in contrast to theory-driven analytic system models in the context of direct-drive EDR simulation is an interesting area of future exploration. The limiting current equation used in this work is an example of a parametric, empirical model. These models for system identification and for limiting current should be rigorously validated in future experimental work.

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community-scale desalination systems. In *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, volume 2, pages 1–5. IEEE, 2019.

Chapter 5

Conclusions

This work presents a novel control scheme which enables near-batteryless electrodialysis desalination. This control scheme is computationally robust and efficient, is simple to implement, and provides the maximum water production rate for any given energy provided. The minimization of model-based control and predictive control facilitates the adaptability of this controller to changes in the system and environment over time: feedwater concentration changes, changes in the desired target conductivity, membrane fouling and degradation, changes in electronic component efficiencies and addition or removal of latent hardware. This work closes a gap between model-based time-variant theory for the operation of electrodialysis systems and practical implementation, while preserving optimality. This work also presents a design framework for minimally sizing energy compensation and understanding coupled trade-offs when designing the control scheme and hardware for a direct-drive system. We demonstrate the validity of this theory with authentic conditions including real groundwater from a well, real solar irradiance, as well as a system built from commercially available hardware. The system operating with our control scheme was able to significantly reduce the battery size of similarly sized systems by 99.4% (from 20 kwh to 120 wh) while maintaining high water production rates and single-day solar utilization rates of 79% and 91%. This direct-drive electrodialysis control scheme greatly reduces and has the potential to fully eliminate the the need for batteries which facilitates simple, minimal-maintenance, and low-cost off-grid electrodialysis desalination.