Technoeconomic feasibility of decentralized desalination in the Navajo Nation

by

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Abstract

The Navajo Nation, located in the southwest United States, faces a significant water stress issue, with approximately 30% of households lacking access to piped water. For many, connection to a piped network is infeasible and decentralized solutions, like desalination, have encountered barriers to adoption. This study evaluates the Navajo Nation's geography, environment, and infrastructure to justify decentralized desalination. A diverse group of stakeholders were interviewed to gain comprehensive insights into the underlying challenges and possible value-added solutions. Analyzing these interviews revealed a cultural aversion to wastewater, a strong sensitivity to operating costs, and two potential system sizes: home and community. With financial sustainability being an important requirement for several stakeholders, a first-order economic analysis of both system sizes was conducted. Home systems present strong potential for economic viability but community systems struggle to compete in this region due to low population density. Using the elucidated design requirements for home systems, electrodialysis (ED) and reverse osmosis (RO) were evaluated for technical feasibility. While RO systems, unlike ED, are commercially available at this scale, RO wastes 50-80% of the feedwater while ED wastes $< 30\%$. Both technologies have strong technical feasibility for this region and both will be field tested to understand long-term maintenance requirements and user perception of wastewater.

Thesis Supervisor: Amos G. Winter IV
Title: Associate Professor

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Chapter 1

Introduction

Water scarcity is a global issue that affects more than a quarter of the world's population [1] and this number is projected to grow as saltwater intrusion affects groundwater supplies [2, 3]. The availability of freshwater is limited, accounting for less than 1% of the global water supply [4]. However, brackish groundwater, which is defined as having 500-10,000 mg/L of total dissolved salts (TDS), presents an opportunity to double available freshwater if properly treated [4]. One region that could benefit from such treatment is the Navajo Nation, located in the southwest of the United States. Considering recent government investment for improving water access in the region [5], this timely study could inform policy decisions.

The Navajo Nation faces significant challenges in accessing clean water, with 30% of households lacking piped water [6]. Due to their remote locations, connecting many of these families to a piped network is infeasible [7]. As a result, families haul tanks of water from scattered, unreliable wells. Accessing water is time-intensive and the poor road conditions lead to high vehicle maintenance costs and gas expenses. When all of these indirect costs are considered, The Navajo Department of Water Resources (DWR) estimates hauling water costs \$0.012-0.035/L compared to \$0.0004-0.0011/L in nearby suburban areas [8, 9].

Decentralized water treatment solutions, like desalination, can provide a good alternative to piped water in remote locations, but the Navajo Nation poses many barriers to adoption. For example, many processes require electrical power but 28%

of homes in the entire Nation lack electricity [10, 11]. Additionally, the poor roads present barriers for frequent maintenance, and contaminants like salt, uranium, and arsenic [12] introduce challenges for managing wastewater. To the authors' knowledge, only one decentralized community desalination system has been piloted in the Navajo Nation [13]. The thermal desalination system was economically unsustainable and failed to achieve a cost per liter of water lower than the current estimates for hauling water [13, 14]. Membrane desalination technologies have been implemented in a few homes, mostly by non-profit organizations, but are not widely adopted despite successful demonstrations around the world at small size scales and off-grid [15–20].

The reasons for slow adoption of decentralized solutions are not well understood, so the first objective for this study is to justify decentralized desalination for this region by identifying locations and sizes of populations that could benefit. The second objective is to understand the design requirements for a decentralized desalination system and evaluate its applicability within the value chain to ensure alignment with all stakeholder needs. The third objective is to conduct a first-order, techno-economic analysis to select a feasible and viable decentralized desalination design positioned for long-term success in the Navajo Nation. Finally, candidate desalination technologies will be evaluated on their ability to meet the design requirements elucidated in the study.

Chapter 2

Justification of Decentralized Desalination

2.1 Market Assessment Methods

For decentralized desalination to be viable in the Navajo Nation, it needs to add value to the community by increasing accessible, potable water sources. It also needs the necessary components to ensure successful operation, like a brackish water supply and renewable energy sources. First, regions with brackish water were identified by interpolating individual well total dissolved salts (TDS) data provided by the United States Geological Survey [21] using the Kriging algorithm in ARCGIS Pro by ESRI. This map was then compared to maps of water scarcity from Aqueduct Water Risk Atlas [22] and number of homes lacking piped water compiled by the Water Access Coordination Group [6] to identify potential markets and their sizes. A map of potential markets was then compared to a map of global horizontal irradiance (GHI) from Global Solar Atlas 2.0 [23] and reported zones of uranium contamination to select and size a target market.

2.2 Potential Markets for Decentralized Desalination

Decentralized desalination can add value by providing more potable water sources in regions with high water stress and brackish water ($500 < \text{TDS} < 10{,}000$) containing numerous homes without piped water. The southern region of Navajo Nation stands out for high and extremely high water stress (Fig. 2-1a). While not labeled as experiencing water stress, the central and west regions are arid with minimal water resources. All of these regions have chapters with hundreds of homes lacking piped water. Several chapters in the north also have over 200 homes without piped water (Fig. 2-1b), however, the salinity map shows low TDS levels in the north (Fig. 2-1c). Meanwhile, the west, south, and center all have brackish water, making them potential markets (2-2) that could benefit from decentralized desalination.

2.3 Target Market for Decentralized Desalination

Potential markets with high solar irradiance and minimal uranium contamination pose a higher likelihood for successful implementation of decentralized solutions. The average global horizontal irradiance is 4.7 kWh/m^2 and most of the Navajo Nation receives average or above average solar irradiance [23]. The west, however, contains a high concentration of abandoned U.S. uranium mines [12, 24]. While desalination could remove these contaminants, wastewater treatment would require special processing, which is prohibitively expensive to implement in remote areas. The western region is excluded from this study due to uranium. The southern and central regions show promise for decentralized desalination to increase potable water access and operate off-grid using solar power (Fig. 2-2). The southern region was selected as the focus for this study based on insights from stakeholder interviews described in the next section that the central region will be connected soon to the piped network.

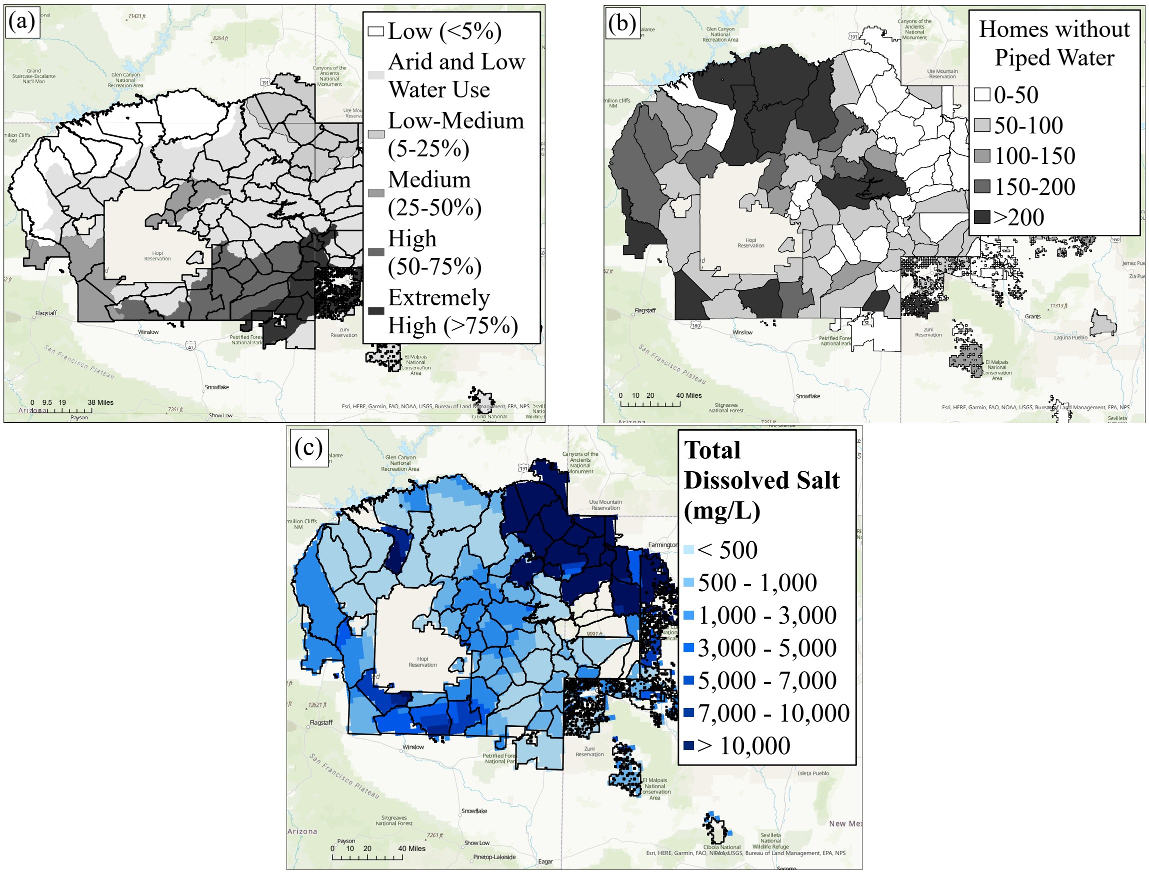

Figure 2-1: Desalination has the potential to provide a significant positive impact in the southern, western, and central Navajo Nation due to high water stress, hundreds of homes lacking piped water, and prevalence of brackish water. (a) Water scarcity in the Navajo Nation provided by the Aqueduct Water Risk Atlas [22]. (b) Homes without piped water compiled by the Water Access Coordination Group [6].(c) TDS levels around the Navajo Nation using interpolated well data from the United States Geological Survey [21].

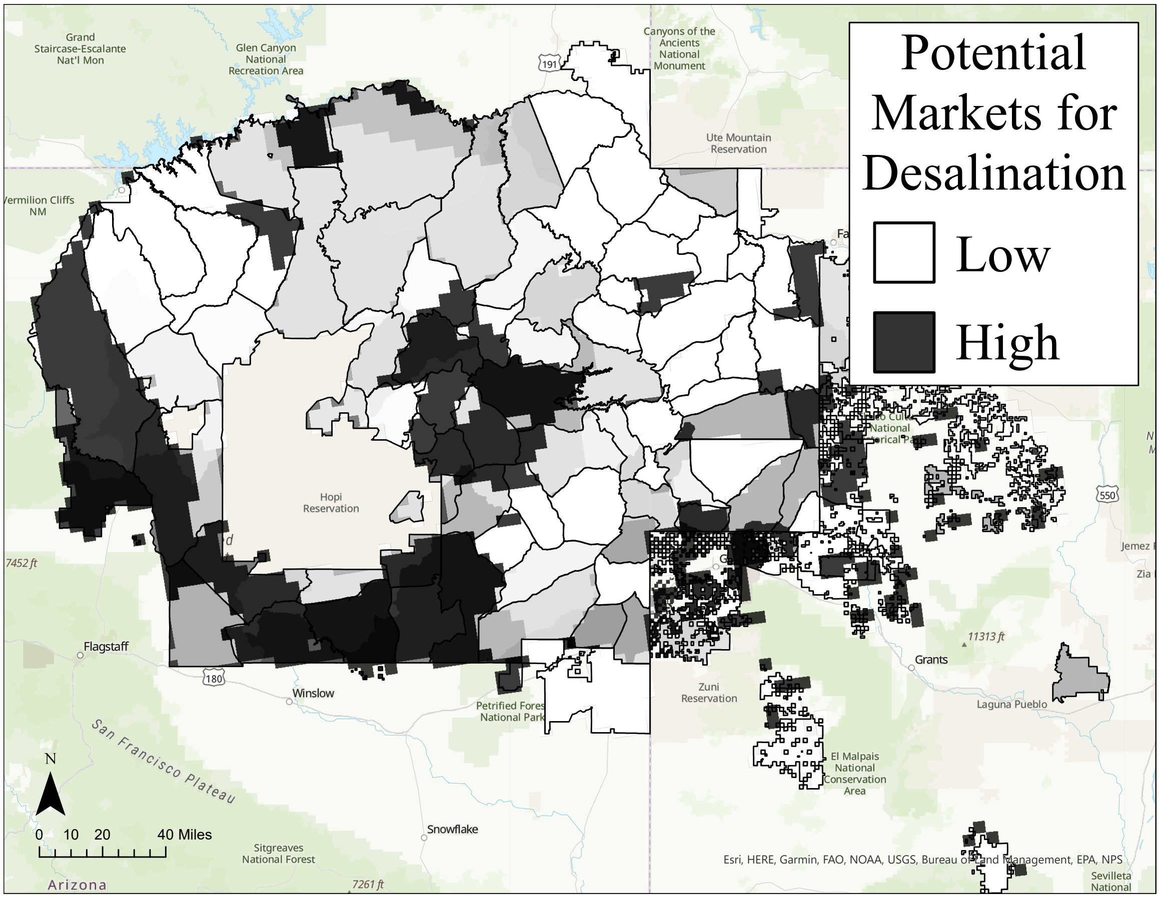

Figure 2-2: Potential markets for decentralized desalination formed by overlaying maps in Fig. 2-1

Chapter 3

Design Requirements and Value Chain Analysis for Desalination in Navajo Nation

To ensure sustainable adoption and retention of a technical solution, diverse stakeholders in the water ecosystem were interviewed to achieve a holistic viewpoint on the root causes of the issue and potential areas of improvement. The analysis of these interviews resulted in a creation of a customer value chain and identification of the primary design requirements for decentralized desalination.

3.1 Stakeholder Interview Methods

A variety of stakeholders in both the U.S. and Navajo government were interviewed since both are engaged with policy and funding of water infrastructure in the Navajo Nation. Additionally, two non-profits were interviewed to learn more about their work to improve water access in the community. Below is a list of the individuals interviewed:

- Water Haulers: 23 from Leupp, Birdsprings, and Indian Wells
- Chapter Officials: Leupp, Birdsprings, Indian Wells, and Round Rock (located

in the central region)

- DWR: Director and head of Technical Construction and Operations
- NTUA: Deputy General Manager and manager of a wastewater facility
- Navajo Nation EPA: Department Manager of Surface and Groundwater Protection
- U.S. Bureau of Reclamation: Program Development Division Manager
- Non-profits: Dig Deep and STAR school

Semi-structured interviews were employed for this stage to focus on qualitative information and deeply understand the issues from multiple perspectives. The study was approved by the Institutional Review Board at MIT and the Navajo Nation Human Research Review Board (NNHRRB). The 1-hr interviews were recorded if participants consented and each household was compensated $20. Written notes and audio were organized under six main topics: water demand, water cost, solution space, reliability, wastewater, and community insights. Patterns were then identified across the different stakeholders' experiences, perspectives, and expertise. A current value chain was constructed based off viewpoints from multiple stakeholders on the workings of the current system (Fig. 3-1a). Then a proposed value chain was formed based on identified trends from interviews about what could provide value to each group (Fig. 3-1b).

3.2 Customer Value Chain

The current value chain revealed an opportunity for desalination to add value for water haulers and the proposed value chain is a possible implementation that addresses all stakeholder needs. While the U.S. Indian Health Services and Bureau of Reclamation provide capital for drilling wells, Navajo organizations fund the operations. The Navajo Tribal Utility Authority (NTUA) oversees wells connected to the piped network that typically need minimal treatment (i.e. chlorine) and the Dept. of Water Resources (DWR) oversees livestock wells that are typically brackish. Currently, non-potable water, represented by the darker water drop in Fig. 3-1, is hauled from livestock wells while potable water, represented by the light water drop, is typically bought at a grocery store or from the chapter house. In the proposed value chain, the desalination unit, either located at homes or at the well itself, allows haulers to get their household and drinking water from one source. Since livestock wells are dispersed around the chapters, this source is typically closer than grocery stores and the chapter houses. Due to recent U.S. government investment [5], funds for purchasing the desalination unit could come from several sources. This could include specific chapters that have economic independence from the Navajo government, which would allow project funding while avoiding a complex bureaucratic process. Operation, maintenance, and replacement (OMR) funds are more difficult to acquire, so both the NTUA and DWR expressed concern about sustaining decentralized systems with their respective team sizes and budgets. This reveals an opportunity for a third-party to maintain these systems, as indicated by red dashed lines in Fig 3-1b. For this third-party to sustain operations, it will likely charge the water hauler but could also receive funding from government entities. STAR school is an example of a third party located outside of Navajo Nation that charges haulers for potable water pumped from a deep aquifer. The non-profit is staffed by volunteers and is a 29 km drive from the nearest chapter house in Leupp on a paved road.

3.3 Design Requirements

Several key findings arose from the stakeholder interviews and led to functional requirements that prioritize reliability, minimize wastewater, and minimize cost (Table 3.1).

From discussing pain points with water haulers, two system sizes emerged as potential solutions. Vandalism of livestock wells motivated 18 people to express a preference for a water treatment system based in their home. Out of those 18 inter-

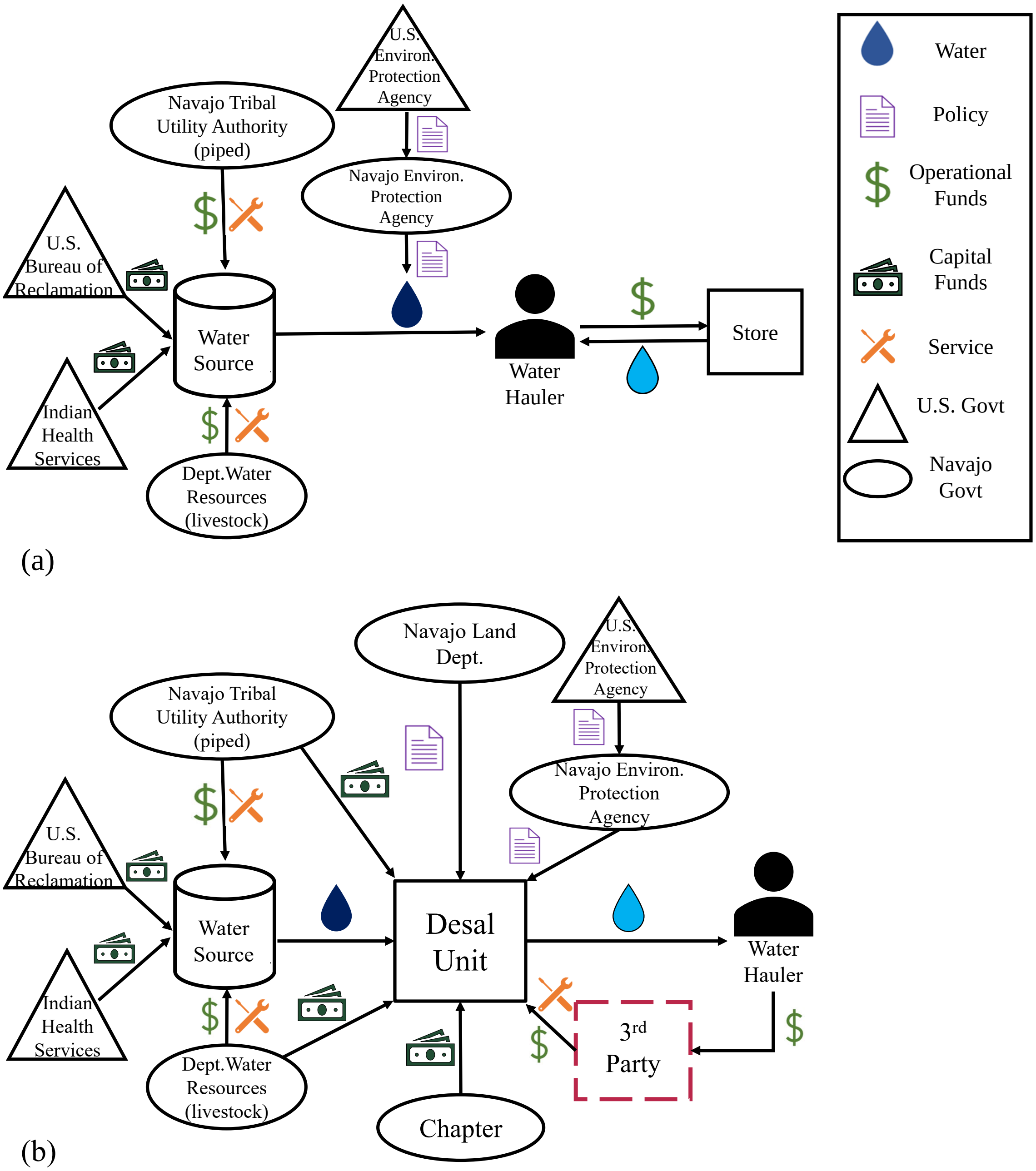

Figure 3-1: (a) Current value chain for drinking water (light blue drop) and household water (dark blue drop) in the Navajo Nation details the funding, service, and policy model in place.(b) The proposed value chain introduces a desalination device to produce drinking water closer for haulers. Due to caution expressed by the NTUA and DWR, a third-party (red dashed lines) can be introduced for maintaining these systems.

viewees, if there was a guarantee of timely maintenance, 12 were also interested in a shared community system based at a livestock well. All 12 voiced economic benefits, as the appealing attribute of community systems is that the costs would be shared with their neighbors. A community system could service a whole chapter, approximately 1,000 people, while a household system could service 1-15 people based on observations during interviews. For both sizes, the production volume reported in Table 3.1 uses the WHO estimation of 19L/day/person. The stakeholder interviews also revealed the strong cultural importance of livestock, and some people haul potable water, not livestock water, for horses. Horses drink at least double the volume of humans, which signals a need for a higher production volume, but some people also haul livestock water for horses and some do not own horses. Additional needs for water, like horses, did not present enough of a pattern to influence the requirement for production volume.

Another cultural attribute emphasized in interviews with every stakeholder was conservative water use. For potential designs, the recovery ratio should be maximized and the brine produced needs to be managed safely and sustainably. Traditional brine treatment methods like evaporation ponds can be used for community systems, but for home-scale evaporation ponds are logistically challenging to implement at every household. To ensure the requirement of safe and sustainable brine is satisfied, ground disposal and dilution for additional uses, are explored as potential alternatives in Sec. 5.

Every stakeholder identified the largest pain point with the current water infrastructure is insufficient maintenance. Much of the inefficiencies stem from a lack of funding leading to a lack of personnel. Capital funds are much easier to acquire with one-time grants than consistent funding for OMR costs. Interviews with the DWR and chapter houses revealed that the government would subsidize the capital cost (as seen in the proposed customer value chain in Fig 3-1b). Since this requirement is relatively insensitive, other cost metrics, OMR and levelized cost of water (LCOW), will be used for evaluating designs. Since OMR funds are difficult to obtain, that cost should be minimized. LCOW is calculated by adding up the total cost, capital and operating, over the lifetime of the system and dividing it by the amount of water produced. It is an important metric for comparing potential designs to each

Table 3.1: Summary of Design Requirements

Design Requirement	Value
Production Volume	19-285 L/day (Home) 570-19,000 L/day (Community)
Recovery Ratio	maximized
Operating Cost	minimized
LCOW	$\leq$ \$0.012/L
Feedwater Salinity	500-5,000 mg/L
Product Salinity	200-500 mg/L
Energy Source	On-grid and Off-grid

other and to the status quo. Interviews with chapter officials revealed the average price of delivering water is \$13/kL and the lowest estimate for hauling is \$12/kL [9]. Eighteen water haulers reported purchasing bottled water from the grocery store and spending approximately \$4 for a pack of forty 0.5 L bottles, which is \$200/kL. To be conservative, the lowest value was used for the design requirement, \$12/kL.

Biological, chemical, and physical water quality are all important requirements for meeting government regulations and user preferences. For biological and chemical, meeting the Navajo EPA requirements is critical for keeping users safe and healthy. Physical water quality has relatively less health consequences but it affects the taste and therefore user preference. Interviews revealed most people purchase bottle water (200-600 mg/L TDS), so the TDS should be less than 500 mg/L to increases chances of user acceptance [25]. Interviews with the Navajo EPA and DWR allowed for lowering the maximum feedwater salinity from 10,000 mg/L (maximum for brackish water) to 5,000 mg/L for the region.

Chapter 4

Economic Viability of Decentralized Desalination in Navajo Nation

To ensure sustainable impact in the Navajo Nation, the selected system and corresponding business model need to be technologically and economically viable. Through analyzing the stakeholder interviews, two potentially viable business models were identified: home-scale and community-scale. The resulting value chain from the stakeholder analysis also highlighted the need for a third-party to maintain and operate these systems. A first-order economic model of basic operational costs was employed to evaluate if either of these business models are non-viable in the Navajo Nation. By only selecting a set of basic costs, this economic model is technologically agnostic so the focus is purely on the viability of the overarching solution path.

4.1 Economic Viability of Home-Scale Desalination

4.1.1 Home-Scale Economics: Methods

The service model for home-scale is modeled after the leading reverse osmosis home installation company in India, Eureka Forbes [26]. They conduct two service visits a year for part replacement and maintenance [26, 27]. To generalize across desalination technologies, only the operator costs (salary, vehicle repair, vehicle depreciation, and fuel) and pre-treatment filter costs were considered, totaling \$50,000 per operator and \$6 annually per system, respectively. For the business to be self-sustaining, the costs must equal the revenue multiplied by a profit margin (Eq. 4.1). There are three main variables in the equation: number of systems (N_{sys}), price charged per service visit ($\frac{price}{visit}$), and number of operators (N_{op}).

$$\begin{aligned} \$50000N_{op} + \$6N_{sys} = (1 - profit\,margin)\times \\ \frac{visits/year}{system} \times N_{sys} \times \frac{price}{visit} \end{aligned} \tag{4.1}$$

The number of systems and number of operators are interdependent since there is a maximum amount of systems an operator can service each year to ensure reliable customer service. To minimize costs, the operators should be fully utilized assuming they work 40 hours/week and 50 weeks/year. The minimum number of operators can be calculated using the number of systems, various ideal maintenance times, and the assumed work schedule. The range of maintenance times (15-120 mins) was selected based on conversations with Eureka Forbes [26]. To assess economic risk, two benchmarks were used: number of homes that have no funding to receive piped water (2,662), the target market, and estimated number of homes without piped water (9,650), the potential market. A profit margin of 13% was selected since the industry standard for water supply and irrigation systems is 13.4% [28].

4.1.2 Home-Scale Economics: Results and Discussion

Figure 4-1 depicts the price per visit that must be charged to achieve a 13% profit margin for different number of systems and maintenance times. Since the number of operators needs to be an integer, all lines overlap at the beginning when only one operator is needed. As the number of systems increase and more operators are needed, a sharp increase in price/visit is observed. To the left of the dashed red line, homes without funding for piped water, is the target market shaded in green. Similarly, to the left of the black dashed line, homes without piped water, is the potential market shaded in yellow.

Several combinations of maintenance times and price per visit exist in both the target and potential market regions. By decreasing the profit margin, all the lines shift down illustrating that a lower price per visit can be charged to maintain the lower profitability. Similarly, by decreasing the service visit frequency to once per year, the lines shift down since fewer operators are needed to support the fleet of systems. Many interviewed water haulers reported purchasing four cases of bottled water every two weeks, totaling \$416/year for drinking water. With a home desalination system, people could pay a fraction of that cost. A better understanding of people's willingness to pay for increased drinking water access is needed to verify long-term economic success, however, home-scale presents strong potential for economic viability in the Navajo Nation and will be further explored in this study.

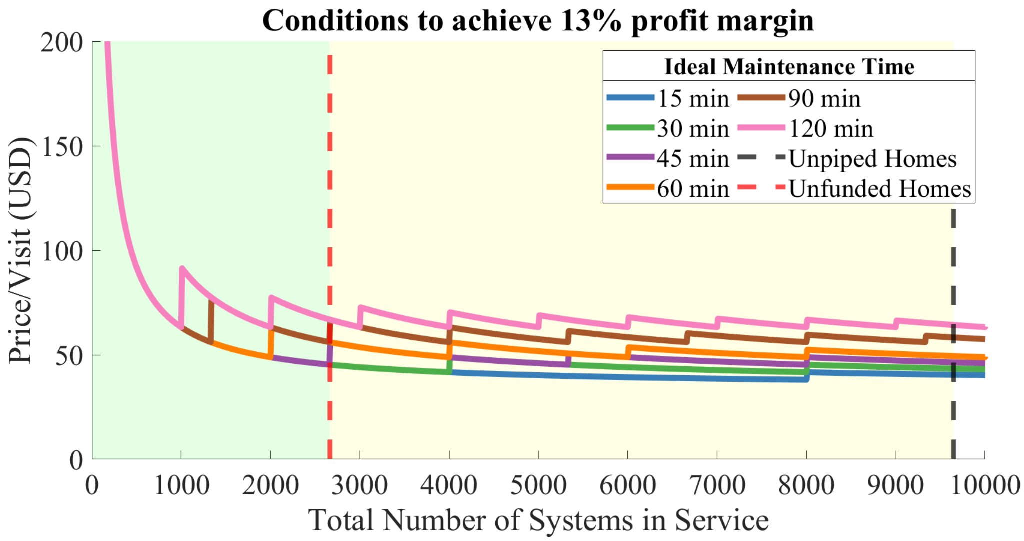

Figure 4-1: Home-scale desalination economic viability. Price per visit that must be charged for different number of systems and various system maintenance times to maintain a 13% profit margin. To the left of the red dashed line is the target market represented by the homes with no funding to receive piped water. To the left of the black dashed line is the potential market represented by the estimated number of homes currently with no piped water.

4.2 Economic Viability of Community-Scale Desalination

4.2.1 Community-Scale Economics: Methods

The three differences in the economic model between community and home systems are the price of pre-treatment filters ($444/year/system), the service model, and the revenue stream. It is assumed that larger systems operating for longer periods of time require frequent maintenance. This model estimates four service visits per year per system and an ideal service time of one hour (30 minutes for maintenance and 30 minutes for driving). Assuming the same work schedule as home-scale, with four system visits per year, the upper limit of the operator bandwidth is 500 systems per year per operator. For community-scale, users will be charged by volume of water, so the revenue depends on the number of users and the amount of water they purchase. The annual amount of water per person (water/person/year) was calculated using the WHO estimate of 19L/day/person. The number of users was calculated by dividing the population density by the system density (Eq. 4.2). In the equation, there are five main variables: number of systems (N_{sys}), water rate in $/kL (*water rate*), number of operators (N_{op}), population density (*pop.density*), and system density (*sys.density*).

$$\begin{aligned} \$50000N_{op} + \$444N_{sys} = (1 - profit\,margin)\times \\ \frac{water/person}{year} \times water\,rate \times \frac{pop.density}{sys.density} \times N_{sys} \end{aligned} \tag{4.2}$$

System density can be understood as the maximum distance a person lives from a system. Assuming the Navajo Nation is divided into a grid with a system in the center of each square, the furthest distance a person would travel is halfway along the diagonal. For example, a constant system density of 1 every 100 km^2 results in the maximum distance of 7 km. Similar to number of operators depending on number of systems, number of systems is limited by system density. Since the Navajo Nation is 71,000 km^2, for a constant system density of 1 every 100 km^2, a maximum of 710 systems can fit within the borders of Navajo Nation. In the ideal case, profit is maximized by maximizing the number of systems given the land area and system density constraints. Similarly, cost is minimized by employing the minimum number of operators to deliver reliable maintenance. For different system densities, the maximum number of systems was calculated then the minimum number of operators needed to support that number of systems was calculated based on the upper limit of the operator bandwidth.

To assess economic non-viability, two benchmarks are used: average population density of homes with no funding for piped water in the southwest region (0.05 ppl/km^2), the target market, and average population density of chapters in the southwest (0.39 ppl/km^2), the potential market. Similar to home-scale, a 13% profit margin was primarily used for this analysis but 5% and 10% were also explored.

4.2.2 Community-Scale Economics: Results and Discussion

Figure 4-2 shows the water rate needed to achieve a 13% profit margin for various population and system densities. Left of the vertical dashed red line, density of homes without funding for piped water, is the target market shaded in green. Similarly, left of the vertical black dashed line, chapter population density, is the potential market shaded in yellow. At low population densities, exponentially higher water rates are needed to support the fleet of systems covering the Navajo Nation. Even though these rates are lower than the LCOW from Sec. 3.3 ($12/kL), a local competitor (STAR school) charges $5.28/kL (horizontal dotted black line). In the target market at or below this price point, community-scale systems are viable at low system densities. However, since the system density and population density are both low in this target market region, the maximum number of people serviced by each system is 30 (0.05 pop. density divided by 1/600 sys. density). Additionally, at these low system densities, less than 100 of these 30-people systems are needed to cover the Navajo Nation. These community-scale systems are equivalent to two home-scale systems yet require people to drive a maximum of 17 km to a centralized location when there is likely a closer well to each individual. In this best-case scenario where systems cover the Navajo Nation, operators are fully utilized, and basic costs are included, community-scale systems struggle to compete.

By decreasing the profit margin, all the lines shift down illustrating that a lower population density is needed to maintain profitability. The shift, however, is small and does not increase economic viability in the target market at competitive prices (below \$5.28/kL). Adjusting the minimum maintenance time required has a negligible effect because the primary limitation is system density not operator bandwidth. Changing these assumptions does not increase the economic viability of community-scale so it will not be explored further due to high economic risk in this region.

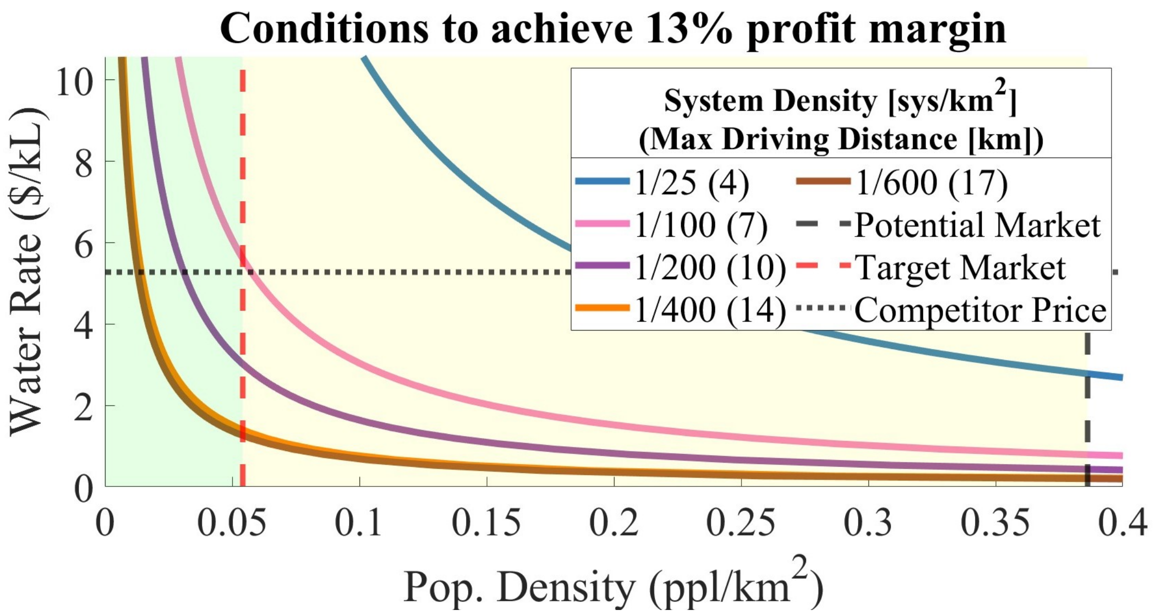

Figure 4-2: Community-scale desalination economic viability. Water rate needed to achieve a 13% profit margin for different population and system densities. Left of the red dashed line is the target market in green and left of the black dashed line is the potential market in yellow.

Chapter 5

Technical Feasibility of Decentralized Desalination in Navajo Nation

Different home-scale desalination technologies were evaluated for feasibility based on their ability to satisfy the requirements detailed in Table 3.1. Only membrane desalination systems were considered because they typically require less frequent maintenance for remote systems than solar distillation [29] and are more conducive to smaller systems than thermal technologies [30]. The three main technologies that have been demonstrated off-grid and small-scale are reverse osmosis (RO), electrodialysis (ED), and nanofiltration (NF) [15–20]. The latter will not be considered due to its inefficiencies extracting monovalent ions [31], the main contaminant in this region, relative to the other two technologies. RO is a pressure-driven technology that extracts contaminants by pushing water through a semi-permeable membrane. ED is an electrically-driven technology that removes charged contaminants by applying a potential across alternating cation and anion exchange membranes resulting in alternate channels of product water and brine.

5.1 Functionality Comparison

At low production volumes, there are no commercially available ED systems. However our research team is developing a system that includes a small ED stack, pre-filtration and UV post-treatment to meet water quality standards. It has only been tested up to 2,500 mg/L so further validation is required for higher salinity feedwater, which may increase costs and affect performance. In bench-top testing, the ED prototype produced drinking water at a rate of 13.5±0.5 LPH with a recovery of 90±3%, which meets both the production volume and recovery ratio requirements.

In comparison, RO systems are widely available at this scale. For this analysis, a 75 GPD or 285L/day system [32] was selected to meet the production volume requirement. Similar to the ED system, it includes pre- and post-treatment to meet water standards but is only rated for TDS less than 2,000 mg/L [32]. To meet the salinity requirement, an RO membrane rated for higher salinities can be exchanged, typically for a higher cost. Unlike ED, the recovery RO membranes can achieve is lower [29, 30], especially at this size-scale. The U.S. EPA reports that typical point-of-use RO systems have a 20% recovery and rarely surpass 50% [33]. While both ED and RO can meet production volume and water quality requirements, only ED satisfies the recovery ratio requirement.

5.2 Brine Remediation Comparison

Recovery was identified as a critical requirement due to the cultural aversion to wasting water, however, the re-usability of the brine could cause the user to not perceive it as waste. A low recovery RO system will produce a relatively higher volume of low salinity brine that could potentially be used for other purposes. Meanwhile, a high recovery ED system will produce a low volume of high salinity brine that may be harder to use. Either method will still produce relatively small volumes of brine when compared to larger scale systems, so the remediation options include: ground disposal, subsurface disposal, and dilution for reuse. Disposing the brine on the surface may disrupt plant growth, which is already minimal in this desert region. In the Californian desert, Glenn et al. [34] watered salt tolerant with brine and experienced success but warns this method depends on the site's aquifer salinity, soil, and irrigation practices. Before implementing salt-tolerant crops, a controlled study and buy-in from the community would need to be completed to ensure long-term success. Disposing the brine subsurface, similar to the depth of outhouses in the region, has not been well studied in the literature but may solve the environmental concern of soil salinization. If all the desalinated water is used for drinking, the user could dispose of the brine in the same place they urinate (i.e. outhouse). The mass and volume would be mostly conserved and there will be a negligible increase in salinity.

For dilution, the salinity increase is the main concern for the next use (i.e. livestock or household use). If a control volume was drawn around a water hauler's tank, a fraction of the water is extracted to produce drinking water while the rest is used in the household or given to livestock. Through the desalination process, a portion of the extracted water will become brine and be returned to tank. The resulting salinity increase (δC_{tank}) depends only on the volume of the tank (V_{tank}), volume of the drinking water produced (V_{prod}), and feedwater salinity (C_{feed}). The derivation of Eq. 5.1 can be found in Appendix B. Based on interviews with water haulers, the smallest tank size is 950 L, so for a mid-range feedwater salinity in this region of 3000 mg/L, product salinity of 300 mg/L, and a weekly production volume for a one-person household (133 L), one can expect a 14.7% increase in salt concentration to 3440 mg/L. This increase in salinity will likely not impact household uses, such as mopping, or livestock health as long as other contaminants, like sulfates, are at safe levels. More consumption data are needed to confirm these results and fully understand potential increases in salinity.

$$\delta C_{tank} = \frac{\frac{V_{tank}C_{feed} - V_{prod}C_{prod}}{V_{tank} - V_{prod}} - C_{feed}}{C_{feed}} \times 100 \tag{5.1}$$

While RO has a lower recovery ratio, if the brine is easier to use, it may not be perceived as wasteful. These options require further testing to ensure there are no negative environmental impacts and to understand user perception.

5.3 Energy Comparison

Most homes that lack piped water also lack electricity, so a solar array will be needed to power the system. Bench-top testing of the ED system reported a specific energy consumption (SEC) of 0.35 kW-hr/kL [27] using 1500 mg/L feedwater. For RO, a study completed by Shah et al. [35] showed for a 60 psi system, the specific energy consumption ranges from 1.8 kW-hr/kL for 650 mg/L feedwater to 2.4 kW-hr/kL for 1800 mg/L feedwater. A lower SEC will decrease the power requirements and therefore the cost of the overall system, which is discussed further in the next section.

5.4 Economic Comparison

RO and ED were evaluated on their ability to meet the two cost metrics discussed in Section 3.3: operating cost and LCOW. Since the systems have the same pre-treatment filters and UV light, these costs were kept the same for both systems. Off-the-shelf values and minimum recommended replacement times from the same company as the RO system [32] were used for the filters ($35, 6 months) and UV light ($41, 12 months). A 80 psi booster pump was selected for the RO system costing $20.74 [36]. Since the ED system requires less pressure, a 55 psi pump costing $11.50 was selected [27]. For both, the pump is assumed to need replacement every five years. RO membranes need to be replaced every two years and ED membranes need to be replaced every ten years [32, 37, 38]. ED also needs acid treatment to ensure the long lifetime of the membrane and was calculated to be $2.10/year for the ED prototype [27]. For on-grid systems, electricity cost was calculated using the system's SEC, max daily production volume, and NTUA rate of $0.074/kW-hr. For off-grid systems, solar panel cost was calculated using the system's SEC, max daily production volume, and estimation of $1/W [39]. For RO, 1.9 kW-hr/kL was used for SEC since it corresponds to 1000 mg/L feedwater. Operating cost includes part replacements and for on-grid systems, electricity cost. The capital cost for the RO system is the commercial price ($279) [32] and includes solar panels for the off-grid system. The capital cost of the ED system ($166) was estimated using off-the-shelf components and standard stack material prices [27]. With an assumed lifetime of 20 years, both ED and RO meet the requirement for LCOW. When the operating cost is compared to buying bottled water ($416/year), both RO and ED are less expensive, with ED being 28% less for on-grid and 26% less for off-grid than RO.

Tech	Power	Capital Cost ($)	Avg. Operating Cost ($/yr)	LCOW ($/kL)
ED	Grid	166.00	119.92	1.237
	Solar	201.99	117.24	1.229
RO	Grid	279.00	151.07	1.590
	Solar	474.36	136.50	1.546

Table 5.1: Cost comparison between ED and RO for off-grid and on-grid

Chapter 6

Discussion

This paper identified a potential market for decentralized desalination that would benefit hundreds of families. Design requirements were successfully elucidated that prioritized cost and reliability, two major pain points based on stakeholder interviews. Using these design requirements, the study evaluated the economic viability and technical feasibility of RO and ED. Community-scale is economically not viable in this region due to low population densities and both ED and RO have merits for home-scale systems.

This study has a few limitations that could impact these findings. Since the semi-structured interviews focused on qualitative information, there is a lack of quantitative data on consumption habits which could impact the economic viability of community-scale. If people are purchasing more drinking water for other uses, such as horses or their household, revenue would increase and community-scale could become more competitive. The second limitation is the lack of quantitative data on willingness to pay. This could impact home-scale viability if people cannot afford the price per visit ($50-100/visit) identified to be profitable in the guaranteed market. While this analysis shows ED to be cheaper for both on-grid and off-grid applications, more information is needed on the maintenance requirements of ED that could result in additional costs. Even though RO has a lower recovery ratio, it will produce lower salinity brine that could be used in other applications so people may not perceive it as wasteful. Future work will pilot both technologies in the Navajo Nation to learn about the long-term maintenance requirements, the true cost to the user, and the user perception of wastewater and recovery ratio.

Although community-scale is not viable for the southern Navajo Nation, our results demonstrate that community-scale could work for areas with higher population densities. Additionally, people in Navajo Nation are water conservative, so in other communities that use more water a community-scale system could be more viable. The increased consumption would also impact the production volume design requirement and potentially target salinity depending on the use of the water, like irrigation. Finally, this study identified a higher sensitivity to operating cost than capital cost but in other communities, the sensitivity may be the opposite. This could affect the selection of the suitable technology. For both researchers and practitioners working with other communities around the world, this study highlights the importance of understanding and working with a community before selecting a solution. While community-scale is a successful design in areas around the world, it would struggle to be a sustainable solution in the Navajo Nation. The combination of user, economic, and technical analysis can give a clearer perspective on technical solutions for a given a community.

Chapter 7

Conclusion

This study identified the southwest region of the Navajo Nation as a target market for decentralized desalination because it contains numerous homes without piped water and has prevalent brackish water and solar irradiance. Stakeholders throughout the value chain were interviewed to understand pain points and solution paths. Analysis of these interviews led to the formation of design requirements for two system sizes: home and community. Findings from the interviews were also used to create a proposed value chain. A third party was included to maintain the systems since established stakeholders lack funding and therefore personnel to manage these systems. By modeling simple operational costs for this third party, community-scale systems were deemed economically non-viable due to low population densities. Home-scale, however, presented strong potential for economical viability, so home RO and ED systems were evaluated for technical feasibility. Both ED and RO confidently meet a subset of the design requirement identified by analyzing stakeholder interviews. Future work will include piloting both technologies in the field to determine the best suited for the region. The insights from this study as well as future field work will provide guidance for implementation of government funds to improve water access in the region.

Appendix A

Water Hauler Interview Questions

Interviews with water haulers were semi-structured and asked questions related to the following topics:

- Typical water hauling trip
- Cost of water hauling
- Willingness to pay for more convenient potable sources
- Perception of a reliable water source
- Wastewater

Appendix B

Dilution Calculations

Section 5.2 discusses methods for brine remediation including dilution for other uses. Understanding the salinity increase when brine is mixed with the leftover brackish feedwater is important for determining the feasibility of this remediation method. This analysis assumes brackish water of concentration C_{feed} is hauled in a tank of volume V_{tank} and only a fraction is extracted to produce drinking water of volume V_{prod} and concentration C_{prod}. The brine produced (V_{brine} and C_{brine}) is then added back into the tank resulting in a salinity increase to C_{new}. Assuming perfect mixing, C_{new} can be calculated using:

$$C_{new} = \frac{(V_{tank} - V_{prod} - V_{brine})C_{feed} + V_{brine}C_{brine}}{V_{tank} - V_{prod}} \tag{B.1}$$

The brine volume and concentration can be rewritten in terms of the recovery ratio (RR), C_{feed}, and C_{prod} as seen below:

$$V_{brine} = V_{prod}(\frac{1}{RR} - 1) \tag{B.2}$$

$$C_{brine} = \frac{C_{feed} - C_{prod}RR}{1 - RR} \tag{B.3}$$

Substituting Eq. B.2 and B.3 into Eq. B.1 and simplifying:

$$C_{new} = \frac{V_{tank}C_{feed} - V_{prod}C_{prod}}{V_{tank} - V_{prod}} \tag{B.4}$$

With this new salinity, the percent increase in salinity of the tank (C_{tank}) can be calculated:

$$\delta C_{tank} = \frac{\frac{V_{tank}C_{feed} - V_{prod}C_{prod}}{V_{tank} - V_{prod}} - C_{feed}}{C_{feed}} \times 100 \tag{B.5}$$

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