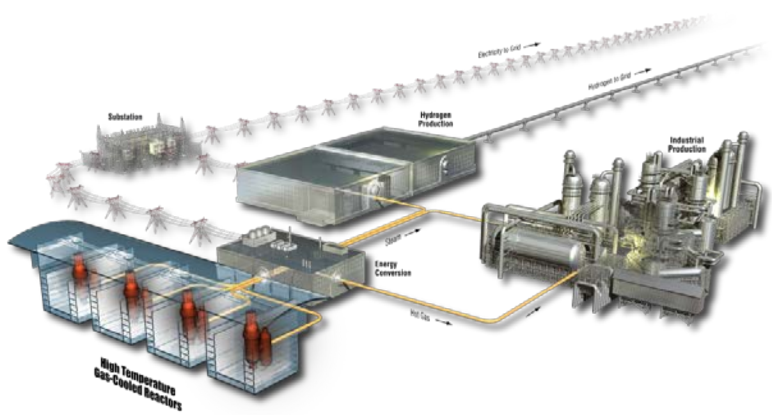
INL/EXT-19- 55736
Revision 1

Case Study: Integrated Nuclear-Driven Water Desalination—Providing Regional Potable Water in Arizona

Aaron Epiney
James Richards
Jason Hansen
Paul Talbot
Pralhad Burli
Cristian Rabiti
Shannon Bragg-Sitton

September 2019



The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

INL/EXT-19- 55736
Revision 1

Case Study:
Integrated Nuclear-Driven Water Desalination—Providing Regional Potable Water in Arizona

Aaron Epiney
James Richards
Jason Hansen
Paul Talbot
Pralhad Burli
Cristian Rabiti
Shannon Bragg-Sitton

September 2019

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

The present study analyzes the economic viability of an Integrated Energy System (IES) that couples a Reverse Osmosis (RO) water desalination facility with a Nuclear Power Plant (NPP). The case study is conducted in collaboration with Arizona Public Service (APS), the operating owner of the Palo Verde Generating Station (PVGS) NPP.

Cooling water for the reactor steam cycle is derived from treated effluent from municipal wastewater treatment plants. APS has established a long-term water resources program to effect a substantial reduction in plant cooling costs through advanced treatment and cooling technologies, and through the use of alternative water sources to replace the increasingly expensive effluent. One possible option is to replace some amount of the annual volume of effluent with brackish groundwater from a local regional aquifer. Although much less expensive than the municipal effluent, the quantity of brackish groundwater that could be used for plant cooling is limited as a result of the salinity and its impact on plant operation. Consequently, supplemental treatment could be required such that a greater amount of brackish groundwater could be used to reduce the demand on effluent. A study was conducted in 2018 by Idaho National Laboratory (INL) to investigate the economics of a PVGS onsite RO desalination plant that would reduce the salinity of a municipal effluent and brackish water blend to an acceptable level. One of the main findings of that study was that the overall economics of water desalination can be greatly improved if, in addition to cooling water for PVGS, potable water could also be produced and sold for profit. In fact, the study concluded that only producing cooling water for PVGS via RO desalination is not economically viable.

The present report investigates the economic impact of a large, regional RO desalination plant that could provide potable water for the region, considering the conclusions from the 2018 scoping study. The study looks in particular at the water-market situation for the developing municipalities in the west valley of Phoenix. In addition to providing potable water for the municipalities, the existing infrastructure that conveys effluent to the Palo Verde plant and onsite water treatment facilities could be used to manage the RO concentrate. The processed concentrate could lead to a cost reduction in plant cooling by replacing some amount of effluent.

The analysis reported here considers two cases (for various scenarios). First, the Base Case considers that neither the regional nor the onsite RO is built. The 2018 INL study showed that some brackish water can be blended with the municipal effluent water without having to build the onsite RO. That correspond to the maximum economically profitable option. The Base Case is where APS pumps the maximum volume of less-expensive brackish water (limited by water chemistry in the circulating water system), i.e. the case for which cooling water acquisition and treatment cost are lowest (without RO). Second, the proposed RO Case includes two RO plants, one onsite at PVGS and another larger, regional RO plant close to the brackish water wells. The regional RO produces potable water that is sold to the regional municipalities, while the PVGS onsite RO treats (part of) the regional ROs' concentrate and brackish water blend. The desalinated water from the PVGS RO is used in the circulating water system at PVGS. The analysis evaluates the difference in economics, using the Net Present Value (NPV) and Internal Rate of Return (IRR), between the cases. By comparing the two cases, in addition to evaluating the economics of the regional RO, we can also assess the impact of the regional RO on PVGS operational costs and, consequently, APS economics.

The study shows that there exist combinations of regional RO and PVGS RO sizes for which the total blowdown and water chemistry limits at PVGS (including regional RO concentrate treatment at PVGS) are satisfied. However, such combinations only exist if no additional brackish water is directly mixed in the tertiary water system at PVGS. This leads to higher Levelized Costs of Potable Water (LCOPW) compared to cases where additional brackish water is injected (but violate the physical constraints). Additional studies are suggested to investigate the benefit of additional brackish water injection (lowers cooling water cost) versus the cost of lifting the physical constraints, e.g. building additional evaporation ponds. Staying in the case of no additional brackish water and satisfying the existing PVGS constraints, the lowest LCOPW (~0.5 $\$/m^3$) can be achieved with a size of the regional RO of ~1.4e7 m^3/yr (11000 AF/yr) capacity, which leads to ~8.63e6 m^3/yr (7000 AF/yr) of potable water while no onsite RO at PVGS is built. Considering the

residential water demand model developed for the Phoenix west valley, the NPV for this regional RO would be ~$100 million if all municipalities in the vicinity participate from the beginning of the project.

CONTENTS

FIGURES

TABLES

ACRONYMS

ADWR	Arizona Department of Water Resources
AF	Acre-foot, acre-feet
APS	Arizona Public Service
BWRO	Brackish Water Reverse Osmosis
CAPEX	Capital expenditure
FE	Fixed Effects
FWP	Feedwater Pump
gpm	Gallons per Minute
HP	High-pressure
HPS	Hassayampa Pump Station
IES	Integrated Energy System
INL	Idaho National Laboratory
IRR	Internal Rate of Return
LCOCT	Levelized Cost of Concentrate Treatment
LCOPW	Levelized Cost of Potable Water
MACRS	Modified Accelerated Cost Recovery System
N-R HES	Nuclear-Renewable Hybrid Energy System
NPP	Nuclear Power Plant
NPV	Net Present Value
O&M	Operation and Maintenance
PPM	Parts Per Million
PV	Palo Verde
PVGS	Palo Verde Generating Station
RAVEN	Risk Analysis Virtual Environment
RE	Random Effects
RO	Reverse Osmosis
RPS	Redhawk Power Station
TDS	Total Dissolved Solids
VRE	Variable Renewable Energy
WACC	Weighted Average Cost of Capital
WRF	Water Reclamation Facility
WRSS	Palo Verde Water Reclamation Supply System
WTP	Wastewater Treatment Plant

Case Study: Integrated Nuclear-Driven Water Desalination—Providing Regional Potable Water in Arizona

1. INTRODUCTION

The present study analyzes the economic viability of an Integrated Energy System (IES) that couples a Reverse Osmosis (RO) water desalination facility with a Nuclear Power Plant (NPP). The case study is conducted in collaboration with Arizona Public Service (APS), the operating owner of the Palo Verde Generating Station (PVGS) NPP.

Palo Verde is the largest nuclear single site facility in the U.S. generating on average 32,000,000 MWh annually. The three Combustion Engineering System 80 - 3990 MWth reactors provide significant grid stability and baseload generation for the southwest and west coast. Sustained growth of renewable generation in this region has resulted in seasonal over-generation and consequential frequent low power pricing. Government subsidized and "must take" renewables challenge baseload facilities to reduce long-term operating costs to remain competitive and provide long-term value to the facility owners and power consumers.

In addition to being the largest domestic nuclear power generating facility, Palo Verde is also the only nuclear facility in the world not located on or near a natural body of water. Cooling water for the reactor steam cycle is derived from treated effluent from municipal wastewater treatment plants in the Phoenix area and is processed at an onsite tertiary treatment facility to plant chemistry standards. Construction of the three Palo Verde units in the 1980s was predicated on an assured supply of municipal effluent.

Population growth, concurrent with sustained drought conditions now challenges the limited natural surface and groundwater reserves, resulting in rising value (and cost) of alternative resources like municipal effluent. Consequently, plant cooling water represents an increasing fractional cost of generation.

APS has established a long-term water resources program to affect a substantial reduction in plant cooling costs through advanced treatment and cooling technologies, and through the use of alternative water sources to replace the increasingly expensive effluent. One possible option is to replace a relatively small amount of the annual volume of effluent with brackish groundwater from the shallow regional aquifer located east of the Palo Verde plant in Buckeye Waterlogged Area (BWLA). The BWLA is the natural geographical low point near the confluence of the Gila, Agua Fria, and Salt Rivers. There is an estimated 300 million acre-feet of sustainable brackish groundwater in the BWLA that could support withdrawal without adverse impact to local agriculture that is dependent upon this supply. Approximately 5,000 to 10,000 acre-ft of the brackish water has been proposed as part of the average annual consumption of approximately 75,000 acre-ft. Use of the BWLA poor quality groundwater would offset the same amount of the better quality effluent which could be put to beneficial use by the west valley cities.

A study was previously conducted in 2018 by Idaho National Laboratory (INL) to investigate the economics of a PVGS onsite RO desalination plant that would reduce the salinity of an effluent and brackish water blend to an acceptable level [1]. The study showed that:

- If the operational target salinity for the PVGS cooling water in the reservoir ponds is strictly enforced at all times (instead of enforcing the limit as an average-over-time), then it is economically beneficial to keep buying municipal effluent water exclusively rather than building an RO plant for any amount of brackish water. There is no economy of scale (i.e., savings made by purchasing more brackish water are roughly offset by the need for increased RO size and the associated capital and operational costs).

- If *time-average chloride concentration* in the water reservoirs is considered as opposed to the maximum, results indicate that no RO is needed for up to ~16000 acre-feet(AF)/year of brackish water blended into the municipal effluent water, or about 20% of the PVGS cooling water needs. Compared to the case where the operational target salinity in the reservoir is strictly enforced, the time-averaged chloride concentration allows the operational target salinity in the water reservoirs to be exceeded for some time. However, the circulating water chemistry limits are respected at all times (by adjusting the blowdown). Furthermore, the RO becomes barely economically viable for additional amounts of brackish water beyond ~16000 AF/year.

In the same study, the argument was made that, to offset some of the desalination cost, desalinated potable water could be sold for profit. That scoping study showed that:

- The Levelized Cost of Potable Water (LCOPW) that offsets the RO cost is likely between ~1.0 $\$/m^3$ and ~1.7 $\$/m^3$. Improved water-market models are needed to assess the possible water demand and supply, and thus to better assess the economically viable band of LCOPW.
- The capacity of the evaporation ponds at PVGS will quickly become the limiting factor for the amount of potable water that can be produced. The evaporation ponds need to be able to accommodate the concentrate from the RO in addition to the blowdown from the PVGS cooling water towers. Therefore, exact blowdown models and evaporation pond capacities will be needed to make a better assessment.

The current report provides results of a more detailed investigation of the economic impact of a large regional RO desalination plant that could provide potable water for the region considering the conclusions from the 2018 scoping study. The study looks in particular at the water-market conditions in the Phoenix west valley municipalities of Buckeye, Goodyear, Avondale and Tolleson (see Figure 1). These communities are considered because of their proximity to the BWLA and access to the Palo Verde Water Reclamation Supply System (WRSS) which could convey the concentrate from a regional facility with the effluent to the Palo Verde Water Resources treatment facility. In addition, this region's future economic growth strongly depends on the availability of clean potable water, which right now is among the most-limiting factors. A regional RO plant that is capable of treatment and concentrate disposal is likely to significantly boost the region's capacity for population, and therefore economic growth.

Figure 1. Phoenix west valley region including PVGS, the municipalities of Buckeye, Goodyear, Avondale, Tolleson and Phoenix downtown [3].

There are significant, sustainable reserves of brackish groundwater in the Phoenix west valley. The water can be put to beneficial use with proper treatment. However, the production of useable water from this regional aquifer also requires disposal of the waste stream (RO concentrate). A regional RO plant that is capable of treatment and disposal is likely to significantly boost the region's capacity for population, and therefore economic growth.

There are limited options for the management of the RO concentrate from a large-scale municipal RO water treatment facility. Deep well injection is improbable in the shallow Phoenix sub-basin and the injection process lacks the required authority in Arizona. Surface evaporation ponds are very expensive and require significant surface area for the scale considered in a regional sized project. However, the Palo Verde plant has 650 acres of lined evaporation ponds that manage the water balance for the zero-liquid discharge facility. Excess capacity in the Palo Verde evaporation ponds, coupled with supplemental treatment, may provide an acceptable alternative for large-scale RO concentrate management provided the Palo Verde water balance can be maintained.

Allowing for the construction of the necessary infrastructure to convey RO concentrate from a regional facility to the Palo Verde Water Reclamation Supply System (WRSS) piping and on to the Palo Verde Water Resources Treatment Plant, the concentrate could be blended with municipal effluent from the Phoenix wastewater treatment plants that serve Palo Verde. The concentrate could be treated onsite at PVGS. Effectively, some portion of the regional RO facility concentrate would be reclaimed through the onsite treatment system. This will reduce the effluent demand, albeit by a small amount, factoring into the overall economic analysis of the regional RO treatment project. The amount of concentrate that may be accommodated at the Palo Verde Water Resources facility (as a blend with municipal effluent and pumped brackish groundwater) is likely to be very small. Consequently, a supplemental RO facility would need to be located onsite at Palo Verde and downstream of the tertiary system. The regional RO and the supplemental onsite RO treatment facility would provide a small increase in APS baseload demand, helping to mitigate potential Variable Renewable Energy (VRE)-induced demand and electricity price volatility. From this perspective, the RO plants can be seen as stabilizing loads on the grid. Although APS can sell its electricity for a fixed retail price (on a cost-recovery basis) to cover the local demand first, it also participates in the California Independent System Operator (CAISO) Energy Imbalance Market. Due to the growing VRE penetration, the PV hub electricity spot price is occasionally negative and is expected to become negative more and more frequently.

To mitigate potential demand and price volatility, APS and INL evaluated two possible strategies in different studies in 2018 and 2019: (1) Adding more baseload, so that the quantity of excess energy to be sold at the hub for prices that are potentially under the internal retail price or even negative prices at the hub is reduced [1] and (2) operating PVGS in a flexible way; i.e., load-following [2]. Both of these analyses (using different electricity demand and hub price forecasting assumptions) showed that the number of hours when APS has to sell excess electricity at the hub or has to load-follow is negligible. The maximum opportunity to absorb negative prices at the hub, either by adding baseload or load-following, is less than 10% of the total revenue of APS electricity sales. Therefore, there is negligible economic benefit associated with the integration of a large-scale regional water treatment center as a strategy to increase base load.

As noted above, the current report now evaluates the economic value of a large-scale desalination (RO) regional treatment facility with concentrate management at Palo Verde in consideration of the cost reduction in plant cooling costs attributed to replacement of some amount of effluent with RO concentrate. The terminal objective is to construct a process water cost function (cost per volume) in consideration of system sizing for the on-site RO supplemental treatment. The maximum production of the regional RO facility will then be determined based on the optimum sizing conditions.

The following analyses have applied the Nuclear-Renewable Hybrid Energy System (N-R HES) software framework, which has been under development at INL since 2016 [4-10]. The framework has reached a level of maturity that allows it to be applied to more than simple demonstration cases; i.e., real industry problems. Nevertheless, more capabilities are constantly added to accommodate the special needs of these challenging real-life problems. The N-R HES framework is built on top of the Risk Analysis Virtual Environment (RAVEN) code [11-13], which it uses as a driver and workflow manager for all calculations. The framework has specifically been developed for the economic assessment of N-R HESs. There are four main cornerstones of the N-R HES simulation framework:

1) generation of stochastic time series,
2) a set of algorithms for probabilistic analysis and optimization in RAVEN,
3) a set of models that represent the physical behavior of N-R HES components and sub-systems, and
4) a RAVEN plugin called CashFlow [7] that maps physical performance into economic performance.

Within this framework, a broad spectrum of questions related to N-R HES can be addressed.

This report provides an initial assessment of the viability of a large-scale RO facility as an integrated energy system (responsive load) as one element of a strategy to avoid curtailment of the Palo Verde units. In addition, the evaluation explores the potential for APS to reduce operating costs while concurrently supporting the long-term water sustainability goals for the Phoenix west valley municipalities. The following describes a possible APS water procurement strategy and lays out the possible regional RO plant scenarios studied in this document (Chapter 2). These proposed scenarios do not reflect any collaborative agreements between Palo Verde (including APS and or the other plant owners), referenced municipalities, the Arizona Department of Water Resources, or any other entity. Chapter 3 then describes the APS case model developed within the N-R HES software framework. Chapter 4 presents all the model input data and assumptions and discusses the simulation results. Finally, Chapter 5 includes the conclusions as well as suggestions for further studies.

2. APS CASE DESCRIPTION

As mentioned in the introduction, a large-scale "regional" desalination (Reverse Osmosis – RO) facility is proposed to serve the future water needs of the growing Phoenix west valley, while providing a potential alternative water source to incrementally reduce the dependence on effluent as the feedstock for cooling water at the PVGS. In this scenario, APS is considering taking and treating the concentrate stream from the regional RO facility to replace some of the (more expensive) effluent. Treatment of the concentrate would be accomplished onsite at PVGS with the help of an additional (small) RO plant. The additional load from the regional RO as well as from the onsite RO will raise the base load in the APS service region, and consequently mitigate some of the demand volatility introduced by increasing amounts of VRE. However, as already investigated [1], due to the relatively small electrical capacities of the ROs compared to the capacity of the PVGS, this effect will be small and is not considered in this study. More importantly, the onsite RO could allow production of lower-cost clean (but not potable) water as needed in the PVGS circulating water system by blending brackish ground water, regional RO concentrate, and municipal effluent water, which would then be processed through the onsite RO, compared to buying 100% of the water from the more expensive municipal effluent that would not require processing through RO. The analysis in this report considers two cases:

- **CASE 0**: CASE 0 represents the Base Case for the present study and corresponds to the most economical case for PVGS cooling water per the findings of the 2018 INL study [1], i.e. the case for which total cooling water acquisition and treatment cost are lowest without considering the regional RO. The 2018 study showed that by enforcing the chloride limit for the PVGS cooling water at all times (instead of enforcing the limit in average-over-time) only a limited volume of brackish groundwater can be used to offset the same amount of effluent (approximately 3% of the total annual requirement). The 2018 report concludes that it is not economically beneficial to build an onsite RO plant for supplemental treatment to increase the amount of groundwater used.

In the Base Case APS pumps the maximum volume brackish water that can be blended with the municipal effluent, where the maximum is set by water chemistry limits in the circulating water system and evaporation pond capacities and no RO is built. It is worth mentioning that all the analysis in the present report assumes time-average chloride concentrations for the operational limits instead of strict maximums.

- **CASE 1**: CASE 1 includes two RO plants, one located onsite at PVGS and a second larger, regional plant sited close to the brackish groundwater wells. The regional RO would produce potable water that is sold to the regional municipalities[1], while the PVGS onsite RO is treating (part of) the regional ROs concentrate and some additional brackish water. The desalinated water from the PVGS RO is used in the circulating water system at PVGS.

The analysis evaluates the difference in economics, in terms of Net Present Value (NPV) and Internal Rate of Return (IRR) between the scenarios. By comparing the two scenarios, in addition to evaluating the economics of the regional RO, we can also assess the impact of the regional RO on PVGS and consequently APS economics. Another benefit of this method is that it only considers the cash flows that actually change between the scenarios to determine the change in the NPV (ΔNPV) (see Section 3.4).

2.1 Base Case (CASE 0)

The current APS water procurement strategy is as follows: secondary-treated effluent is supplied by local municipalities and is delivered to the PVGS WRSS piping. The treated effluent is conveyed through the 36-mile WRSS piping system and arrives at the PVGS Water Reclamation Facility (WRF), where tertiary treatment is performed to achieve the water quality needed for the steam cycle cooling (circulating water) system. Steam cycle cooling is ultimately provided by evaporation in large mechanical draft cooling towers at PVGS. In addition, some of the tertiary treated water is also piped to the nearby APS-owned Redhawk Power Station (RPS). RPS consists of two, identical, 500 MW natural gas-fueled combined-cycle units. Redhawk uses the treated effluent purchased from PVGS to meet its cooling needs.

The municipal effluent chemistry varies seasonally. Hardness cations such as Magnesium and Calcium increase in the winter months whereas chlorides increase in the summer months. The limiting constituent determines how the water balance is managed to ensure that scaling of steam cycle heat transfer surfaces (plant condenser) does not occur, and that concrete structures are structurally maintained. In addition, the concentration of Total Dissolved Solids (TDS) in the circulating water system (and cooling towers) must be maintained to preclude exceeding atmospheric dispersion limits resulting from cooling tower drift. The WRF reduces the effluent hardness to acceptable concentration through the addition of lime and soda ash, and by acid addition to maintain pH. The most important impurities treated by the WRF are silica, calcium, magnesium, sodium, and sulfates, as well as total alkalinity.

The WRF tertiary process does not reduce the chloride content in the water. Chloride limits are maintained in the circulating water system through continuous discharge (blowdown) of a small amount of the circulating water system inventory to the plant's 650 acre evaporation ponds. The amount of blowdown is adjusted to ensure that the water cycle balance is maintained while minimizing the burden on the evaporation ponds. For the purposes of this evaluation, it will be assumed that all chemical constituents

[1] For the purposes of this evaluation, it is assumed that the revenue derived from the production of potable water offsets production and treatment costs and balance provides revenue against Palo Verde operating power production costs. A more plausible scenario involves a collaborative agreement with the local municipalities to construct the facility and to support municipal operation. Production cost for potable water distribution within the cities is based on facility capital investment and concentrate management costs, in addition to the operating and maintenance costs required of the municipalities.

with the exception of chlorides are either non-limiting in terms of cycles of concentration or can be maintained through lime and soda ash dosing in the tertiary system. As noted above, chlorides concentration will then be maintained in the circulating water system and cooling towers by varying the amount of system blowdown.

As discussed previously, the 2018 INL report [1] concluded that some brackish groundwater from the local aquifer can be blended with the municipal effluent water without having to build an onsite RO to supplement tertiary treatment and reduce chloride concentration. The blended effluent and brackish groundwater is treated in the WRF to reduce all chemicals except chlorides. Since the blended water will have a higher chloride content than the pure effluent, system blowdown will increase. The Base Case will evaluate the maximum amount of brackish water that can be blended with effluent so that the chloride content of the blend water can still be managed by increased blowdown (instead of having to desalinate the water via RO). The limit of brackish water that can be blended will likely be set by the evaporation ponds' capacity for accepting blowdown water. This scenario is shown in Figure 2. As one can see, brackish water is blended with effluent, but no RO is built onsite at PVGS.

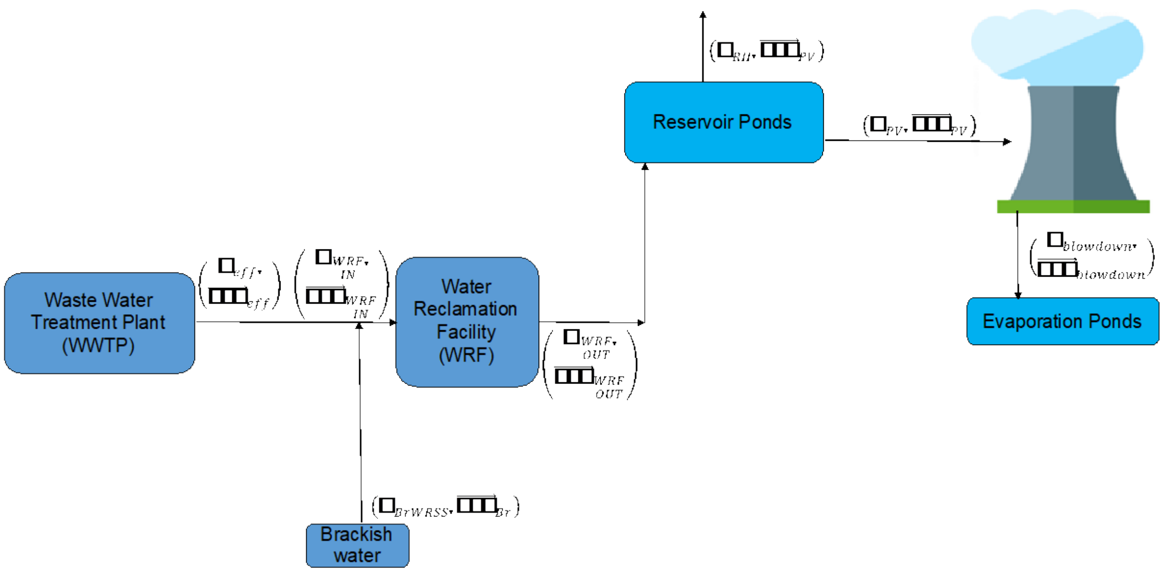


Figure 2. CASE 0: Effluent and brackish groundwater is blended and used at PVGS for cooling. The amount of brackish water is limited such that no additional RO treatment is needed. Symbols used in the figure are described later in Section 3.1.

2.2 Regional RO Desalination for Potable Water (CASE 1)

CASE 1 considers building a regional RO desalination plant (designated RO2) near the brackish water wells, which are located in the Phoenix west valley area, that will supply the neighboring municipalities with potable water. Note that the analyzed strategy will consider RO as a baseline desalination technology, while other technologies may also be available. Building a regional RO near the brackish water wells implies dealing with the problem that there are no evaporation ponds (and likely no space to build ponds) to accommodate the waste stream from the RO.

Since APS is looking for alternative economical water sources, it is proposed that the owner/operator of the regional RO can inject the waste stream from the regional RO into the existing WRSS piping and convey it to PVGS for disposal. APS would then treat the blend of effluent, brackish, and waste (concentrate) from the regional RO with another onsite RO (designated RO1) at PVGS. The cost of water treatment would be passed on to (or at least shared with) the owner of the regional RO.

This case is shown in Figure 3. The WRF can reduce almost all major dissolved solids in the effluent water, with the exception of chlorides. The brackish water and waste from the regional RO contain a much higher amount of chlorides than the effluent water; hence, the resulting blend of effluent and brackish water may have a chloride concentration above the operational target for the reservoir ponds. The effluent, brackish, and wastewater blend is first treated by the existing WRF, and then a fraction (α) of the WRF tertiary treated water is treated by a to-be-built onsite RO. The rest of the water is directly diverted to the reservoir ponds, where it mixes with the treated water from the RO. The RO is capable of treating the water to a much cleaner level than needed by the PVGS cooling system, α; therefore, the capacity of the RO is determined such that the quality of the mixed water in the reservoir is above the threshold for PVGS and the RPS.

In summary, the alternative scenario (CASE 1) considers building two ROs, one near the brackish water wells (RO2) and one at the PVGS site (RO1). This configuration avoids the need for evaporation ponds at the location of RO2. APS can reduce the amount of effluent water purchased by using the RO2 wastewater, but the salinity of the blended effluent and waste from the brackish water RO2 will likely be too high for the cooling system and would need treatment. Therefore, to reduce the salinity to a limit that the water can be used in the circulating water system, a second RO is likely needed. This additional RO1 unit can be built at the PVGS site where evaporation ponds are already available.

For the purposes of this evaluation, the onsite RO1 can only be placed downstream of the WRF tertiary system and not downstream of the PVGS circulating water system and cooling towers; i.e., in the blowdown. Although it would likely be more efficient to treat the PVGS blowdown with the RO and recycle that water into the circulating water system, regulation restricts water from the cooling tower cycle from being reintroduced in the water reservoirs. If the RO treatment is performed in the cooling tower cycle without the possibility to mix it back into the water reservoirs, the water salinity in the reservoirs (which would be the high-saline effluent, brackish, and concentrate blend) would likely be over the limit acceptable by the RPS.

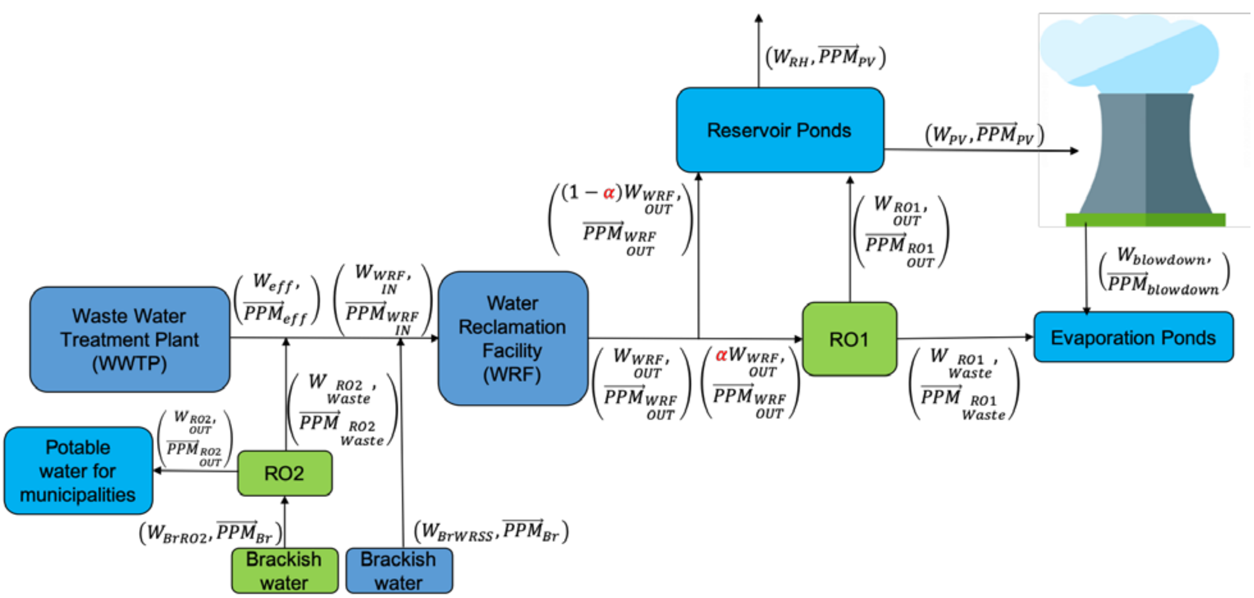


Figure 3. CASE 1: Effluent brackish water is pumped from the ground. Some of the brackish water is purified and sold, while the waste and some of the brackish water is blended with the effluent. This mix

needs to be treated in an onsite RO added to the WRF. Symbols used in the figure are described later in Section 3.1.

3. MODEL DESCRIPTION

This section describes how the two APS cases described in Section 2 are modeled. In general, both cases are modeled within the N-R HES software framework, where the framework provides some generic capabilities that can be used to build the case-specific models. Some nomenclature is introduced before taking a closer look into the model itself.

3.1 Nomenclature

This section summarizes the general nomenclature used for the APS case model within the N-R HES framework. It should be noted that the models and equations presented in the report may use different units (Imperial, SI, chemical concentrations in dissolved ions or as equivalent of some other quantity, etc.) as is most convenient for each calculation. The equations are implemented in the model as presented, but the unit transformations performed are not presented here to simplify reading of the equations.

Facilities naming

WRF	Water Reclamation Facility
RO1	Reverse osmosis plant to be located at PVGS onsite, located downstream of the WRF
RO2	Large regional reverse osmosis plant to be located in the west valley
PumpWRSS	Pumping facility to inject brackish water in the pipeline in the west valley
PumpRO2	Pumping facility for brackish water to be desalinated in RO2

Indexes

j	Index for years (1…J)
i	Index for month in year (1…12)
J	NPP residual life; this is an input for the model (NumberOfYears in Table 2)

Facilities characterization (WRF)

$W_{\underset{IN}{WRF}}$	WRF inflow [kg/month]
$W_{\underset{OUT}{WRF}}$	WRF treated water outflow [kg/month]
$\overrightarrow{PPM}_{\underset{IN}{WRF}}$	Chemistry of WRF inlet water (concentration of 6 tracked chemicals in [ppm])
$\overrightarrow{PPM}_{\underset{OUT}{WRF}}$	Chemistry of WRF outlet water (concentration of 6 tracked chemicals in [ppm])
$PPM_{cal\underset{OUT}{WRF}}$	WRF outlet calcium concentration (as $CaCO_3$) [ppm]
$PPM_{mag\underset{OUT}{WRF}}$	WRF outlet magnesium concentration (as $CaCO_3$) [ppm]

$PPM_{sodWRF_{IN}}$ WRF inlet sodium concentration [ppm]
$PPM_{sodWRF_{OUT}}$ WRF outlet sodium concentration [ppm]
$PPM_{alkWRF_{OUT}}$ WRF outlet total alkalinity (as $CaCO_3$) [ppm]
$PPM_{cl^-WRF_{IN}}$ WRF inlet chloride concentration [ppm]
$PPM_{cl^-WRF_{OUT}}$ WRF outlet chloride concentration [ppm]
$PPM_{sulWRF_{OUT}}$ WRF outlet sulfate concentration [ppm]
E_{WRF} Electricity consumption function for the WRF [MWh/month]
F_{WRF} Fixed cost of WRF [$/capacity]
V_{WRF} Variable (and fixed) cost function of the WRF, excluding electricity [$/volume]
$CAPEX_{WRF}$ Unit capital cost of WRF [$/capacity]

Facilities characterization (RO1)

C_{RO1} Capacity of RO1 [kg/s]
$W_{RO1_{OUT}}$ RO1-treated clean water (permeate) [kg/month]
$W_{RO1_{Waste}}$ RO1 waste stream [kg/s]
$\overrightarrow{PPM}_{RO1_{OUT}}$ Chemistry of clean RO1 outlet (permeate) water (concentration of 6 tracked chemicals in [ppm])
$\overrightarrow{PPM}_{RO1_{Waste}}$ Chemistry of RO1 wastewater (concentration of 6 tracked chemicals in [ppm])
E_{RO1} Electricity consumption function for RO1 [Wh/month]
F_{RO1} Fixed cost for RO1 [$/capacity (kg/s)]
V_{RO1} Variable cost function for RO1 excluding electricity [$/volume]
$CAPEX_{RO1}$ Unit capital cost for RO1 [$/capacity (kg/s)]; this is an input for the model (CAPEX_RO in Table 2)

Facilities characterization (RO2)

C_{RO2} Capacity of RO2 [kg/s]
$W_{RO2_{OUT}}$ RO2-treated clean water (permeate) [kg/s]
$W_{RO2_{Waste}}$ RO2 waste stream [kg/s]
$\overrightarrow{PPM}_{RO2_{OUT}}$ Chemistry of clean RO2 outlet (permeate) water (concentration of 6 tracked chemicals in [ppm])
$\overrightarrow{PPM}_{RO2_{Waste}}$ Chemistry of RO2 wastewater (concentration of 6 tracked chemicals in [ppm])
E_{RO2} Electricity consumption function for RO2 [Wh/month]
F_{RO2} Fixed cost for RO2 [$/capacity (kg/s)]
V_{RO2} Variable cost function for RO2, excluding electricity [$/volume]
$CAPEX_{RO2}$ Unit capital cost for RO2 [$/capacity (kg/s)]; this is an input for the model (CAPEX_RO in Table 2)

Facilities characterization (reservoir, cooling tower and evaporation pond)

W_{PV} PVGS cooling water needs (i.e., water flow) at the inlet of the circulating water system [kg/month]. This varies with time, e.g. seasonally

$\overrightarrow{PPM}_{PV}$	PVGS cooling water chemistry at the inlet of the circulating water system (concentration of 6 tracked chemicals in [ppm])
W_{RH}	RPS cooling water needs [kg/month]; this is an input for the model (CoolingRH in Table 1)
$BlowD$	Percentage of water blown down from the PVGS circulating water system to the evaporation ponds at 450 ppm chloride concentration [%]; this is an input the model (Blowdown in Table 1)
$W_{blowdown}$	Water blown down from the PVGS circulating water system to the evaporation ponds [kg/month]
W_{EvCool}	Water evaporated in the PVGS cooling towers [kg/month]; this is an input to the model (CoolingPVGS in Table 1)
W_{EvP}	Water inflow to the evaporation ponds [kg/month]
$\overrightarrow{PPM}_{blowdown}$	Water chemistry blown down from the PVGS circulating water system to the evaporation ponds (concentration of 6 tracked chemicals in [ppm])

Facilities characterization (brackish water pumping station for RO2)

$C_{PumpRO2}$	Capacity of the brackish water pump [kg/s]
$E_{PumpRO2}$	Electricity consumption function for the brackish water pump [kWh/month]
$F_{PumpRO2}$	Fixed cost for brackish water pump [$/capacity (kg/s)]
$V_{PumpRO2}$	Variable cost function of the brackish water pump, excluding electricity [$/volume]
$CAPEX_{PumpRO2}$	Unit capital cost for brackish water pump [$/capacity (kg/s)]; this is an input to the model (CAPEX_Pumps in Table 2)

Facilities characterization (brackish water pumping station for injection in WRSS piping)

$C_{PumpWRSS}$	Capacity of the brackish water pump [kg/s]
$E_{PumpWRSS}$	Electricity consumption function for the brackish water pump [kWh/month]
$F_{PumpWRSS}$	Fixed cost for brackish water pump [$/capacity (kg/s)]
$V_{PumpWRSS}$	Variable cost function of the brackish water pump, excluding electricity [$/volume]
$CAPEX_{PumpWRSS}$	Unit capital cost for brackish water pump [$/capacity (kg/s)]; this is an input to the model (CAPEX_Pumps in Table 2)

Global quantities

$P_{E,W}$	Wholesale electricity price [$/MWh]; this is an input to the model (EL_wholesale_price in Table 2)
$P_{E,R}$	Retail electricity price [$/MWh]; this is an input to the model (EL_wholesale_price + EL_RetWholeDiff in Table 2)
P_{Br}	Price of brackish water [$/acre-foot (AF)]; this is an input to the model (PBrackish in Table 2)
P_{eff}	Price structure of effluent water [$/AF], including multiple tiers and a dependency on the year; this is an input to the model (PEffluent in Table 2)
$Penalty$	The non-usage fee paid for water not used [$]
$WACC_{APS}$	Weighted Average Cost of Capital (WACC) (APS) [%]; this is an input to the model (WACC_APS in Table 2)
$WACC_{RO2}$	WACC (RO2) [%]; this is an input to the model (WACC_RO2 in Table 2)
Inf	Projected inflation rate [%]; this is an input to the model (Inflation in Table 2)
Tax	Corporate tax rate [%]; this is an input to the model (Tax in Table 2)

D_j	Depreciation % at year j [%]; this is an input to the model (See Table 2)
α	Fraction of water outgoing from the WRF to RO1 [%]; this is a constant for a given evaluation of the model (RO1_split in Table 1)
W_{eff}	Effluent water purchased from the municipalities [kg/month]; this is not an input, but has to be solved for a given set of inputs
$\overrightarrow{PPM}_{eff}$	Chemistry of effluent water (concentration of 6 tracked chemicals in [ppm]); this is an input to the model (Chem_cal_eff, Chem_mag_eff, Chem_sod_eff, Chem_alk_eff, Chem_clo_eff, Chem_sul_eff in Table 1). Different values by month can be input
W_{BrRO2}	Brackish water pumped from ground water [kg/month] to be used in RO2; this is an input to the model (W_brackishRO2 in Table 1). Different values by month can be input
W_{BrWRSS}	Brackish water pumped from ground water [kg/month] directly injected into the WRSS; this is an input to the model (W_brackishWRSS in Table 1). Different values by month can be input
$\overrightarrow{PPM}_{Br}$	Chemistry of brackish water (concentration of 6 tracked chemicals in [ppm]); this is an input to the model (Chem_cal_brackish, Chem_mag_brackish, Chem_sod_brackish, Chem_alk_brackish, Chem_clo_brackish, Chem_sul_brackish in Table 1). Different values by month can be input. The chemistry of the brackish water is assumed to be the same for W_{BrRO2} and W_{BrWRSS}
$NPP_{Variable}$	Variable cost of the PVGS NPP [$/production]
NPP_{Fixed}	Fixed cost of the PVGS NPP [$/capacity]
$PowAPS\%$	Share of PVGS belonging to APS [%]; this is an input to the model (PowAPS% in Table 2)

3.2 Overall Data Flow

Figure 4 shows the overall data flow of the APS cases as modeled in the N-R HES framework. A beginning "sampler" in RAVEN provides all the inputs needed by the subsequent models. A list of all inputs for the physics model are given in Table 1. This "sampler" can be any sampler available in RAVEN; e.g., a "Grid Sampler" to run sensitivity studies on the inputs or an optimizer to find an optimal set of inputs with respect to a target variable, such as the maximum NPV. The sampled inputs are then distributed to the subsequent models in the framework. The economics are treated by the RAVEN CashFlow plugin ("NPV" in Figure 4) and its inputs are collected in a separate input file (see Section 4.1).

For the APS cases, the first model run by the framework is the one that computes the physics of the system; i.e., tracks the water quantities and chemical compositions from the water acquisition points through the WRF and RO to the PVGS circulating water system and finally into the evaporation ponds. This physical model is shown in Figure 4 as "APS model" and described in more detail in Section 3.3.

Next, the NPV pre-processor ("NPV PreP" in Figure 4) is run. This module will compute the cash flow drivers needed by the NPV modules. "NPV PreP" receives the outputs from the APS model; i.e., water mass flows and chemical compositions of the water at different points in the system and derives the cash flow drivers from them. Finally, the cash-flow drivers are passed to the NPV modules. The NPV module computes all the cash flows from the input cash-flow drivers, applies taxation, inflation if needed, and discounts the cash flows to finally compute the economic figures of merit (i.e., NPV, IRR, LCOPW, etc.). The NPV module runs multiple times to evaluate the economics figures of merit for APS (Levelized Cost of Concentrate Treatment (LCOCT)) and separately for the owner/operator of RO2 (LCOPW, NPV, IRR) considering different scenarios. Table 2 summarizes the inputs needed for the NPV module; i.e., the economics inputs to the model. The "NPV PreP" NPV modules, including all the cash flows considered in this problem as well as the economic figures considered, are described in detail in Section 3.4.

Finally, the outputs of the NPV modules are passed back to the sampler in RAVEN. For parametric studies on the inputs, the results are simply stored in a file together with the inputs for further analysis and visualization. If the sampler is an optimizer the results are used to construct a gradient, and then a decision is made as to how the inputs need to be changed to move toward a more optimal solution. The optimizer iterates until it converges on the optimum, or the maximum number of iterations is reached. The inputs and outputs for all iteration steps of the optimizer are stored in a file for subsequent visualization.

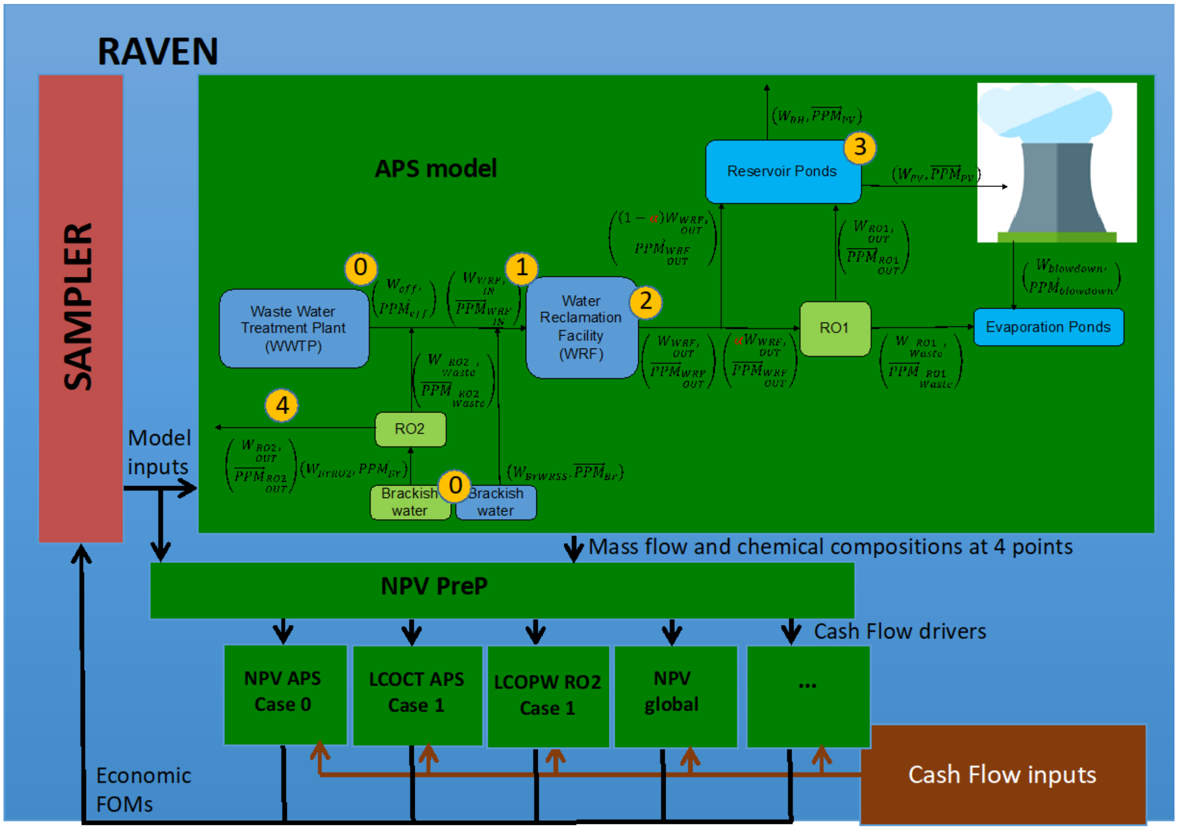


Figure 4. Data flow of the APS case model inside the N-R HES software framework.

3.3 APS Model

As described, the physics of the system are computed by the "APS model" in the software framework. The "APS model" tracks the water quantities (mass flows) and chemical composition through the system from the water acquisition point to the circulating water system and eventually evaporation ponds. The time discretization for all variables is monthly. The concentrations (in ppm) of six different dissolved solids are tracked explicitly in the model ($\overrightarrow{PPM}$), while silica are assumed to be maintained within limits providing magnesium and calcium are maintained in the tertiary treatment process. The explicitly tracked dissolved solids are:

- Calcium
- Magnesium
- Sodium
- Total Alkalinity

- Chloride
- Sulfate.

Table 1: Model inputs for the water model.

Variable name in model	Description	Unit
RO1_split	The percentage of water that goes to the RO after the WRF (α in Figure 3).	%
Blowdown	The percentage of water that goes from the circulating water system to the evaporation ponds.	%
W_brackishRO2	Amount of brackish water purified in RO2. 12 different values; one for every month can be input.	kg
W_brackishWRSS	Amount of brackish water blend with the municipal effluent water. 12 different values; one for every month can be input.	kg
Chem_cal_brackish	Calcium concentration in brackish water.	ppm
Chem_mag_brackish	Magnesium concentration in brackish water.	ppm
Chem_sod_brackish	Sodium concentration in brackish water.	ppm
Chem_alk_brackish	Total alkalinity (as $CaCO_3$) in brackish water.	ppm
Chem_clo_brackish	Chloride concentration in brackish water.	ppm
Chem_sul_brackish	Sulfate concentration (as SO_4) in brackish water.	ppm
CoolingPVGS	Amount of cooing water needed. This is the water evaporated by the PVGS cooling towers; i.e., does not include the blowdown. 12 different values, one for every month, can be input.	kg
CoolingRH	Amount of cooing water needed. This is the total water needed by RPS. 12 different values, one for every month, can be input.	kg
Chem_cal_eff	Calcium concentration (as $CaCO_3$) in effluent water. 12 different values, one for every month, can be input.	ppm
Chem_mag_eff	Magnesium concentration (as $CaCO_3$) in effluent water. 12 different values, one for every month, can be input.	ppm
Chem_sod_eff	Sodium concentration in effluent water. 12 different values, one for every month, can be input.	ppm
Chem_alk_eff	Total alkalinity (as $CaCO_3$) in effluent water. 12 different values, one for every month, can be input.	ppm

Chem_clo_eff	Chloride concentration in effluent water. 12 different values, one for every month, can be input.	ppm
Chem_sul_eff	Sulfate concentration in effluent water. 12 different values, one for every month, can be input.	ppm

Table 2: Model inputs for the economics evaluation (CashFlow inputs).

Variable name in model	**Description**	**Unit**
WACC_RO2	Weighted Average Cost of Capital (WACC); i.e., discount rate for RO2.	%
WACC_APS	Weighted Average Cost of Capital (WACC); i.e., discount rate for APS.	%
Inflation	Inflation.	%
Tax	Corporate tax rate.	%
Depreciation_RO	Depreciation scheme for the RO plants. Modified Accelerated Cost Recovery System (MACRS) schemes for tax depreciation are used.	Property class lifetimes
CAPEX_RO	Unit capital cost for the RO plants.	$/capacity (kg/s)
Depreciation_Pumps	Depreciation scheme for the RO plants. MACRS schemes for tax depreciation are used.	Property class lifetimes
CAPEX_Pumps	Unit capital cost for the brackish water pump.	$/capacity (kg/s)
NumberOfYears	The number of years considered in the Cash Flow calculation for the global project lifetime.	years
PowAPS%	Share of APS at PVGS.	%
EL_wholesale_price	Retail electricity price.	$/MWh
EL_RetWholeDiff	Difference between retail and wholesale price.	$/MWh
PBrackish	Brackish water price.	$/AF
PEffluent	Effluent water price. This is a tired-price structure with a non-usage penalty.	$/AF

The inputs to the model are:

- The cooling water evaporated by the PVGS cooling towers (W_{EvCool}).
- The total cooling water needed by the RPS (W_{RH}).
- The effluent water chemistry; i.e., the concentrations of the six above-mentioned chemicals ($\overrightarrow{PPM}_{eff}$) at the WTP.

- The amount of brackish water pumped for RO2 (W_{BrRO2}).
- The amount of brackish water pumped directly into the WRSS (W_{BrWRSS}).
- The brackish water chemistry; i.e., the concentrations of the six above-mentioned chemicals ($\overrightarrow{PPM}_{Br}$) at the brackish water pumps.
- Alpha (α), the percentage of water (the slipstream) of the cooling water that is treated by RO1.

Looking at the above model inputs, one can see that W_{EvCool} (and consequently W_{PV}) and W_{RH} are inputs, while W_{eff} is an unknown. Ideally, the transfer functions of the RO and WRF can be inverted and the system can be solved using backward induction; i.e., starting from the cooling towers (point 3 (W_{PV}) in Figure 4) and going back to the water acquisition points (point 0 (W_{eff}) in Figure 4). Unfortunately, the system is not analytically invertible and has to be solved iteratively. The "fsolve" root finding algorithm which is a function for referencing the MINPACK subroutine [14], has been used to find W_{eff} for the above inputs. Therefore, the system's equations are implemented in a "forward" manner from the water acquisition (point 0 in Figure 4) to the evaporation ponds (point 3 in Figure 4), and then subject to the solver.

The "reservoir ponds" are not modeled in this version of the APS model. It is assumed that the monthly production of cooling water matches exactly the PVGS cooling water needs for each month ($W_{PV,i} = W_{\underset{OUT}{RO1,i}} + (\alpha - 1)W_{\underset{OUT}{WRF,i}}, \forall i$) and there is no possibility to store produced water between months. This assumption is grounded in the fact that the reservoir ponds could be used as short-term buffers, but likely not in the monthly timeframe, which allows solution of the problem for each month independently; i.e., $W_{eff,i}$ can be found solely as a function of the above inputs at month "i."

3.3.1 Physics Model

All needed cash-flow drivers (electricity consumption, mass flow rate, etc.) can be computed when the mass flow rate and chemical composition of the water at the four points indicated in Figure 4 are known (see numbers 0-4 in "APS model" in Figure 4).

Point 0

The first point where knowledge of the water flow is needed is at the water source. In particular, the effluent water characteristics at the WTP outlet (W_{eff} and $\overrightarrow{PPM}_{eff}$) and the water characteristics at the brackish water pumps (W_{BrRO2}, W_{BrWRSS} and $\overrightarrow{PPM}_{Br}$) must be known. As mentioned, W_{BrRO2}, W_{BrWRSS}, $\overrightarrow{PPM}_{Br}$ and $\overrightarrow{PPM}_{eff}$ are inputs while W_{eff} is found iteratively.

Points 1 and 4

The next point at which knowledge of the water characteristics is needed is point 1 in Figure 4 ($W_{\underset{IN}{WRF}}$ and $\overrightarrow{PPM}_{\underset{IN}{WRF}}$). There are two cases: (1) when RO2 is not present (CASE 0), and (2) the RO2 and associated brackish water pump (CASE 1) are included.

If RO2 is not present (i.e., in CASE 0 where the brackish water is directly injected into the WRSS), water conditions at the WRF inlet (point 1) are as follows:

$$W_1^{CASE0} = W_{\underset{IN}{WRF}} = W_{eff} + W_{BrWRSS} \tag{1}$$

$$\overrightarrow{PPM}_1^{CASE0} = \overrightarrow{PPM}_{\underset{IN}{WRF}} = \frac{\overrightarrow{PPM}_{eff}W_{eff} + \overrightarrow{PPM}_{Br}W_{BrWRSS}}{W_{eff} + W_{BrWRSS}}. \tag{2}$$

In the case where RO2 is present (i.e., CASE 1) some of the brackish water is first treated in the RO2 and the waste stream is then injected into the WRSS, while the permeate clean water can be sold for profit. Therefore, to compute the water characteristics at point 1, we first need to find the water characteristics at the outlet of RO2 (permeate and waste stream). For that we use the RO transfer functions ($f_{transfer\ RO}$), (see Section 3.3.2). The capacity of RO2 is the maximum brackish water mass flow it sees during the year, per the following:

$$C_{RO2} = \max_i (W_{BrRO2,i}). \tag{3}$$

Knowing C_{RO2}, the permeate conditions (which are the water characteristics at point 4 in Figure 4) can be obtained as

$$W_4 = W_{\substack{RO2 \\ OUT}} = f_{transfer\ RO}(W_{BrRO2}, \overrightarrow{PPM}_{Br}, C_{RO2}) \tag{4}$$

$$\overrightarrow{PPM}_4 = \overrightarrow{PPM}_{\substack{RO2 \\ OUT}} = f_{transfer\ RO}(W_{BrRO2}, \overrightarrow{PPM}_{Br}, C_{RO2}). \tag{5}$$

Furthermore, the wastewater characteristics for RO2 can also be found with:

$$W_{\substack{RO2 \\ Waste}} = f_{transfer\ RO}(W_{BrRO2}, \overrightarrow{PPM}_{Br}, C_{RO2}) \tag{6}$$

$$\overrightarrow{PPM}_{\substack{RO2 \\ Waste}} = f_{transfer\ RO}\left(W_{BrRO2}, \overrightarrow{PPM}_{Br}, C_{RO2}\right). \tag{7}$$

Finally, knowing the RO2 wastewater characteristics, the water conditions at point 1 for CASE 1 can be found as follows:

$$W_1^{CASE1} = W_{\substack{WRF \\ IN}} = W_{eff} + W_{\substack{RO2 \\ Waste}} + W_{BrWRSS} \tag{8}$$

$$\overrightarrow{PPM}_1^{CASE1} = \overrightarrow{PPM}_{\substack{WRF \\ IN}} = \frac{\overrightarrow{PPM}_{eff} W_{eff} + \overrightarrow{PPM}_{\substack{RO2 \\ Waste}} W_{\substack{RO2 \\ Waste}} + \overrightarrow{PPM}_{Br} W_{BrWRSS}}{W_{eff} + W_{\substack{RO2 \\ Waste}} + W_{BrWRSS}}. \tag{9}$$

Point 2

Next, the water characteristics at point 2 (i.e., at the WRF outlet) need to be determined. The WRF transfer function is used ($f_{transfer\ WRF}$) (see Section 3.3.3):

$$W_2 = W_{\substack{WRF \\ OUT}} = f_{transfer\ WRF}\left(W_{\substack{WRF \\ IN}}, \overrightarrow{PPM}_{\substack{WRF \\ IN}}\right) \tag{10}$$

$$\overrightarrow{PPM}_2 = \overrightarrow{PPM}_{\substack{WRF \\ OUT}} = f_{transfer\ WRF}\left(W_{\substack{WRF \\ IN}}, \overrightarrow{PPM}_{\substack{WRF \\ IN}}\right) \tag{11}$$

Point 3

Finally, the water characteristics at the PVGS circulating water system must be calculated (point 3 in Figure 4, W_{PV} and $\overrightarrow{PPM}_{PV}$). Two cases exist: (1) CASE 0 where RO1 is not present and (2) CASE 1 where RO1 is built.

In the case where RO1 is not present, the PVGS cooling tower water chemistry is the same as at the WRF outlet, as follows:

$$\overrightarrow{PPM}_3^{CASE0} = \overrightarrow{PPM}_{PV} = \overrightarrow{PPM}_{\substack{WRF \\ OUT}} \tag{12}$$

The mass flow into the PVGS circulating water system is simply the water provided by the WRF minus the water requirements at the RPS:

$$W_3^{CASE0} = W_{PV} = W_{\substack{WRF \\ OUT}} - W_{RH} \tag{13}$$

In the case where RO1 is present (CASE 1), to compute the water characteristics at point 3 we first need to find the water characteristics at the outlet of RO1 (permeate and waste stream). For that we use the RO transfer function ($f_{\text{transfer RO}}$) defined in Section 3.3.2. First, the capacity of RO1 (C_{RO1}) is found so that the RO1 permeate together with the water mixed back from the WRF outlet can satisfy the PVGS cooling tower needs at all times. Intuitively, this condition should happen for $\max_i(W_{PV,i})$, but the RO efficiency is non-linear and a larger RO could be needed for less W_{PV} (considering the increased water need (more blowdown) for higher salinity). Therefore, the capacity of RO1 is solved iteratively.

Once C_{RO1} is known, the permeate conditions can be obtained as:

$$W_{\substack{RO1\\OUT}} = f_{transfer\ RO}(\alpha W_{\substack{WRF\\OUT}}, \overrightarrow{PPM}_{\substack{WRF\\OUT}}, C_{RO1}) \tag{14}$$

$$\overrightarrow{PPM}_{\substack{RO1\\OUT}} = f_{transfer\ RO}(\alpha W_{\substack{WRF\\OUT}}, \overrightarrow{PPM}_{\substack{WRF\\OUT}}, C_{RO1}). \tag{15}$$

Similarly, the waste water characteristics for RO1 are found with:

$$W_{\substack{RO1\\Waste}} = f_{transfer\ RO}(\alpha W_{\substack{WRF\\OUT}}, \overrightarrow{PPM}_{\substack{WRF\\OUT}}, C_{RO1}) \tag{16}$$

$$\overrightarrow{PPM}_{\substack{RO1\\Waste}} = f_{transfer\ RO}\left(\alpha W_{\substack{WRF\\OUT}}, \overrightarrow{PPM}_{\substack{WRF\\OUT}}, C_{RO1}\right). \tag{17}$$

Finally, knowing the RO1 water characteristics, the water conditions at point 3 for CASE 1 can be found as:

$$W_3^{CASE1} = W_{PV} = (1-\alpha)W_{\substack{WRF\\OUT}} + W_{\substack{RO1\\OUT}} - W_{RH} \tag{18}$$

$$\overrightarrow{\mathrm{PPM}}_3^{\mathrm{CASE1}} = \overrightarrow{\mathrm{PPM}}_{\mathrm{PV}} = \frac{\overrightarrow{\mathrm{PPM}}_{\substack{\mathrm{WRF}\\\mathrm{OUT}}}(1-\alpha)\mathrm{W}_{\substack{\mathrm{WRF}\\\mathrm{OUT}}} + \overrightarrow{\mathrm{PPM}}_{\substack{\mathrm{RO1}\\\mathrm{OUT}}}\mathrm{W}_{\substack{\mathrm{RO1}\\\mathrm{OUT}}}}{(1-\alpha)\mathrm{W}_{\substack{\mathrm{WRF}\\\mathrm{OUT}}} + \mathrm{W}_{\substack{\mathrm{RO1}\\\mathrm{OUT}}}}. \tag{19}$$

Blowdown and Evaporation Ponds

The equations described above allow finding W_{PV} and $\overrightarrow{\mathrm{PPM}}_{\mathrm{PV}}$ (at point 3) for a given W_{eff}. As mentioned, W_{eff} is the variable solved for, while W_{EvCool} is the input. The relation between W_{EvCool} and W_{PV} is described in this section. The iterative solver will adjust W_{eff} until W_{PV} found with the equations above is identical to W_{PV} derived from the input W_{EvCool}. At that point, W_{eff} is converged and the system solution found.

The current version of the APS model allows for flexible chloride concentration at the circulating water system inlet. For chloride concentrations lower than 450 ppm, the model uses the input water quantities; i.e., there is no gain in water consumption for lower chloride concentrations. “Blowdown” is the water extracted from the circulating water loop into the evaporation ponds to maintain acceptable chemistry limits in the system. The blowdown is a percentage ($BlowD$) of the water going into the circulating water system (W_{PV}); therefore, the blowdown mass flow $W_{blowdown}$ expressed as function of the input evaporation W_{EvCool} is:

$$\text{For } PPM_{\mathrm{PV}} \leq 450ppm,\ W_{blowdown} = \frac{W_{EvCool} \cdot BlowD/100}{(1-BlowD/100)}. \tag{20}$$

On the other hand, if the input chloride concentration is larger than 450 ppm, the water blowdown for the circulating water system is scaled linearly as follows:

$$\text{For } PPM_{\mathrm{PV}} > 450ppm,\ W_{blowdown} = \frac{W_{EvCool} \cdot BlowD/100}{(1-BlowD/100)} \cdot \frac{PPM_{\mathrm{PV}}}{450}. \tag{21}$$

The water needed at the inlet of the circulating water system can then be found by:

$$W_{PV} = W_{EvCool} + W_{blowdown} \tag{22}$$

In addition, the total amount of water going to the evaporation points is computed as follows:

$$W_{EvP} = W_{\substack{RO1 \\ Waste}} + W_{blowdown} \tag{23}$$

3.3.2 Reverse Osmosis Model

This section is dedicated to the description of the RO desalination plant (or simply referred to as an "RO plant") model used in this study. The model used is the same as the one developed for the 2018 study and described in detail in Reference [1]. A short summary of the model is given here for the readers convenience. The study uses a low-fidelity representation (a surrogate model correlating main inputs to the outputs needed in the present study) of the physical behavior of the RO plant that is based on a high-fidelity model [15-17]. The high-fidelity model is a full dynamic representation of all internal systems (pumps, membrane, valves, plant control system etc.). The high-fidelity system has a large run-time compared to the surrogate. A short system overview of the proposed RO plant for the APS case study is also provided.

RO desalination utilizes a semi-permeable membrane that allows water to pass through but not salts, thus separating the fresh water from the saline feed water. A typical Brackish Water RO (BWRO) plant (see Figure 5(a)) consists of four main components: feedwater pretreatment High-Pressure (HP) pumping, membrane separation, and permeate (fresh water) post-treatment. Figure 5(b) depicts the configuration of an RO vessel (a multi-element module) used in RO desalination, which is typically comprised of six to eight membrane modules connected in series. The concentrate water rejected by the first membrane module plays a role as the feed water for the second membrane module by the successive order, and so on. These pressure vessels are arranged in rows in each membrane stage, with two-stage membrane separation being typical in BWRO. Each stage has a recovery of 50–60%, achieving overall system recovery of 70–85% [18].

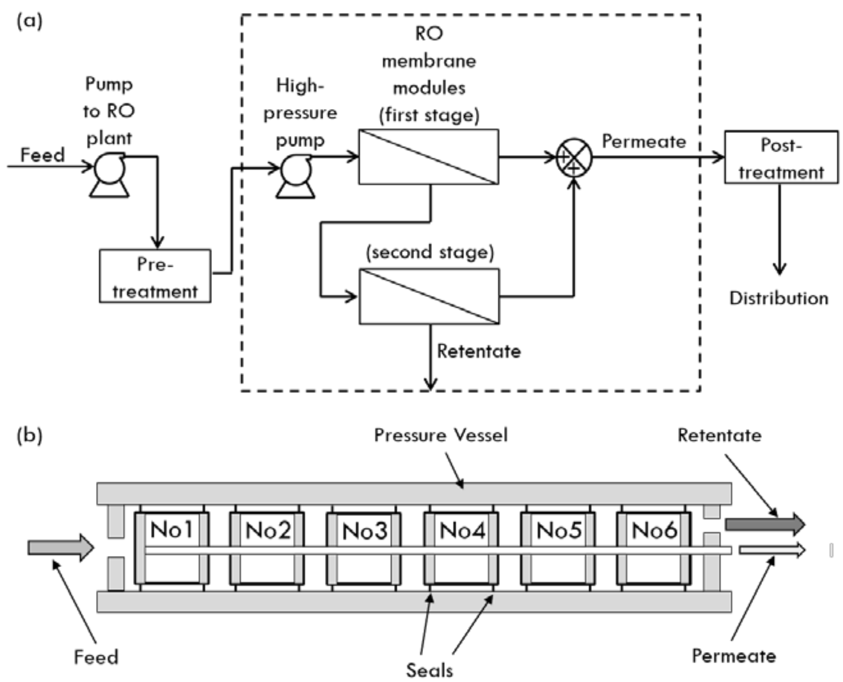


Figure 5. RO desalination: (a) process-flow diagram for a two-stage BWRO plant and (b) schematic of an RO vessel, which consists of six membrane modules in series [16].

Researchers at INL proposed a detailed dynamic modeling and control design of a two-stage BWRO plant, in which the modeling efforts were focused on the two main components: HP pumping and membrane separation units (enclosed in the dashed rectangle shown in Figure 5(a)) [15-17, 19, 20]. In this report, this high-fidelity model served as a starting point for deriving a low-fidelity representation of the proposed BWRO plant; additional assumptions and simplifications made for the APS case study are as follows:

- HP pumping accounts for 90.4% of the total energy consumption in the BWRO facility; i.e., an RO pretreatment system accounts for 9.6% of the total energy consumption in the BWRO facility.
- The system dynamics are, relatively speaking, much faster than the sampling rate (i.e., one hour); thus, steady-state assumption is valid.
- Feed water may contain up to six solids (solutes): bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), and sulfate ($SO4^{2-}$).

The plant was sized for 698 m^3 hr^{-1} (4.43×10^6 gallons per day), which requires 402 kW_e of electrical power to generate the required feed (operating) pressure (12 barg) for desalting the brackish water, containing 900 ppm of Total Dissolved Solids (TDS). Table 3 reports the nominal design specifications of the proposed BWRO plant. The plant model includes the off-the-shelf-available FilmTech 8 in BW30-400 membrane [16]; i.e., a spiral-wound module manufactured by Dow Chemical.

Table 3: BWRO plant specifications.

Symbol	Description	Unit	Value
ε_{pump}	Pump efficiency	%	80
ω	Pump shaft rotational speed	rpm	2240
V_{op}	Valve opening of the pneumatic pressure control valve	%	80
N_{VE}	Number of pressure vessels per HP pump	–	110
N_{ST}	Number of stages	–	2
N_M	Number of RO modules per one pressure vessel (or stage)	–	6
T_f	Feed temperature	°C	25
S_f	Feed salinity	ppm	900
p_f	Feed (operating) pressure	barg	12
p_p	Permeate pressure	barg	0
Q_p	Permeate volumetric flow rate	m^3 hr^{-1}	698
		[gal day^{-1}]	[4.43×10^6]
P_{BWRO}	Rated electrical load in the BWRO plant	kW_e	402
$\bar{S}_p$	Average permeate salinity (quality)	ppm	16.8
R_S	Salt rejection	%	99.4
R_{w1}	Water recovery in the first stage	%	47
R_{w2}	Water recovery in the second stage	%	62
R_w	Overall water recovery	%	80

A high-fidelity model (i.e., Modelica model) might provide an accurate reflection of reality but requires high computational power; thus, an approximation model (i.e., surrogate model) that mimics the behavior of the high-fidelity model as closely as possible, while being computationally efficient to evaluate, is constructed. The proposed system was dynamically modeled with high fidelity with the Modelica modeling language [21] using the commercially available Modelica-based modeling and simulation environment; i.e., Dymola version 2017 FD01 [22]. Then, a linear regressor was proposed to characterize the relationship shown in Eq. 24 between the feed flow rate m_f (i.e., a decision variable set by RAVEN) and the power consumption in the Feedwater Pump (FWP) P_{FWP} (in W_e):

$$P_{FWP} = k_0 + k_1 m_f \tag{24}$$

where k_1 and k_0 are the model-fitting parameters. Several Modelica simulations were conducted to estimate the model estimates by linear regression. Regression results for Eq. 24 are plotted in Figure 6. The estimated model-fitting parameters and the goodness-of-model-fit (R^2 value) are listed in Table 4. Note that the simulation results showed that the dependency of the feed salinity S_f on P_{FWP} is negligible; hence, feed salinity was not considered in Eq. 24. Visually inspecting Figure 6, the quality of the surrogate-model-fits compared to the Modelica model outputs indicates very good model fits.

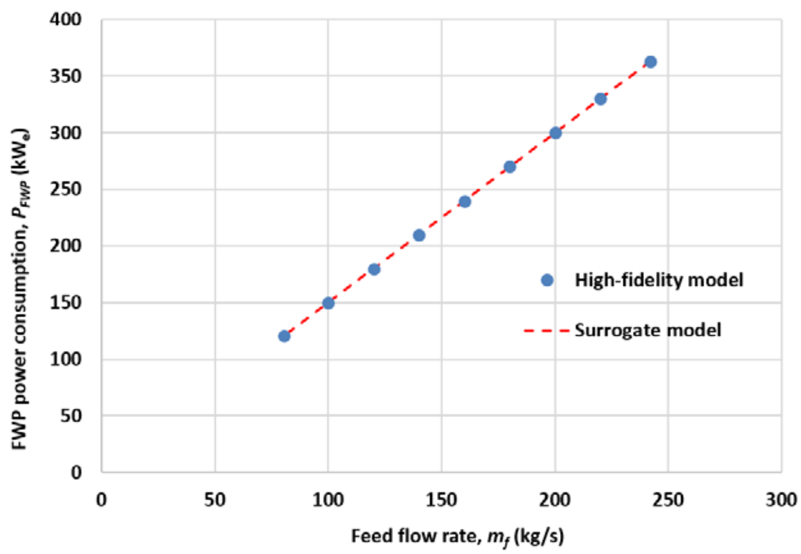


Figure 6. FWP power consumption (P_{FWP}) predicted by the high-fidelity (blue points) and surrogate (red-dashed-line) models.

Table 4: Model parameter estimates for Eq. 24.

Symbol	Description	Unit	Value
k_0	Model parameter	W_e	2.886×10^{-1}
k_1	Model parameter	W_e s kg^{-1}	1.500×10^{3}
R^2	Goodness of fit	–	1.000

As mentioned in the previous section, HP pumping only accounts for 90.4% of the total energy consumption in the BWRO facility P_{BWRO}; therefore, Eq. 25 is proposed to estimate the total energy consumption in the plant:

$$P_{BWRO} = {P_{FWP}}/{0.904} \tag{25}$$

Figure 7 and Figure 8 show the permeate flow rate m_p and salinity S_p, respectively, simulated by the high-fidelity model as functions of feed-stream conditions. In these examples, an osmotic pressure correction factor F_π, defined by Eq. 28, was set to be 1.

As can see in Figure 7, the permeate flow rate increases as the feed flow rate increases for any given feed salinity. Also, at a given feed flow rate, it is expected to produce more permeate water with lower feed salinity. In Figure 8, the results show that the permeate salinity is inversely proportional to the feed flow rate (or equivalently the permeate flow rate) for any given feed salinity. In other words, the higher the feed flow rate, the purer the permeate stream. On the other hand, at a given feed flow rate, the permeate quality (or salt rejection) worsens as the feed salinity increases.

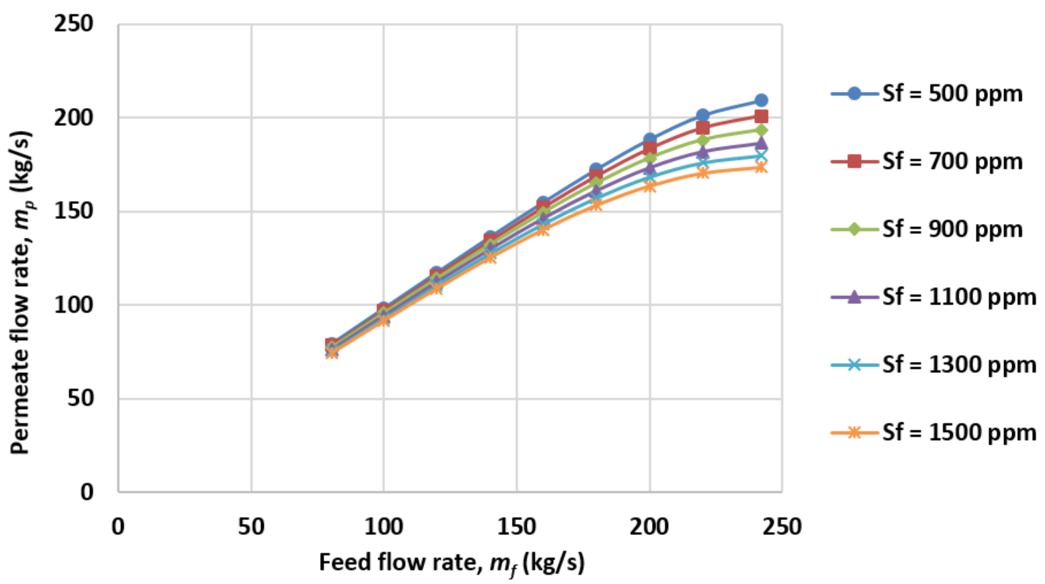


Figure 7. Permeate flow rate (m_p) versus feed flow rate (m_f) simulated for a range of feed salinity (S_f) using the high-fidelity model.

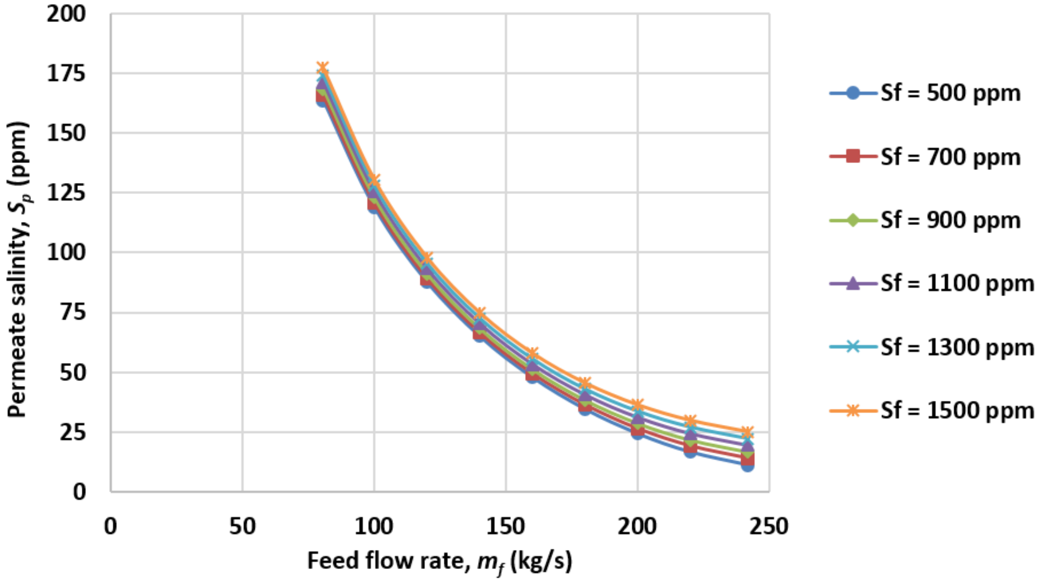


Figure 8. Permeate salinity (S_p) versus feed flow rate (m_f) simulated for a range of feed salinity (S_f) using the high-fidelity model.

In order to predict the permeate flow rate (in kg s^{-1}), the following set of equations is proposed:

$$m_p = k_0 + k_1 m_f + k_2 S_f + k_3 F_\pi + k_4 m_f S_f + k_5 m_f F_\pi + k_6 S_f F_\pi + k_7 m_f^2 + k_8 S_f^2 + k_9 F_\pi^2 \tag{26}$$

$$S_f = \sum_i C_{f,i} \tag{27}$$

$$F_\pi = \frac{\sum_i \frac{S_{f,i}}{MW_i} z_i}{\frac{S_f}{MW_{NaCl}} 2} \tag{28}$$

where k_0–k_9 are the model-fitting parameters, $S_{f,i}$ is the solute concentration of species i in the feed, MW_i is the molecular weight of species i, z_i is the number of valence electrons associated with species i, and MW_{NaCl} is the molecular weight of sodium chloride. The correction factor (F_π) takes into account the difference between the medium containing multiple solids (up to six solutes) and the medium containing only Na^+ and Cl^- for the same concentration of TDS in the feed. Similarly, Eq. 29 is proposed to approximate the permeate salinity (in ppm) as a function of feed stream conditions. The estimated model-fitting parameters and R^2 values are listed in Table 5.

$$S_p = k_0 + k_1 m_f + k_2 S_f + k_3 F_\pi + k_4 m_f S_f + k_5 m_f F_\pi + k_6 S_f F_\pi + k_7 m_f^2 + k_8 S_f^2 + k_9 F_\pi^2 \tag{29}$$

Table 5: Model parameter estimates for Eqs. 26 and 29.

Symbol	Description	Eq. (26)	Eq. (29)

		Unit	Value	Unit	Value
k_0	Model parameter	kg s^{-1}	-68.25	ppm	7.041×10^{2}
k_1	Model parameter	–	1.828	ppm s kg^{-1}	-4.427
k_2	Model parameter	kg s^{-1} ppm^{-1}	2.684×10^{-2}	–	3.482×10^{-3}
k_3	Model parameter	kg s^{-1}	29.03	ppm	-4.151×10^{2}
k_4	Model parameter	ppm^{-1}	-1.820×10^{-4}	s kg^{-1}	1.007×10^{-5}
k_5	Model parameter	–	-1.966×10^{-1}	ppm s kg^{-1}	1.148
k_6	Model parameter	kg s^{-1} ppm^{-1}	-1.614×10^{-2}	–	3.376×10^{-3}
k_7	Model parameter	s kg^{-1}	-2.227×10^{-3}	ppm s^2 kg^{-2}	7.386×10^{-3}
k_8	Model parameter	kg s^{-1} ppm^{-2}	5.758×10^{-7}	ppm^{-1}	1.587×10^{-6}
k_9	Model parameter	kg s^{-1}	7.562×10^{-1}	ppm	85.38
R^2	Goodness of fit	–	0.998	–	0.991

3.3.3 WRF Model

For the WRF transfer function, it is assumed that all chemical concentrations can be reduced to a fixed value, except chloride, which is passed through (i.e., not changed) by the WRF. The values to which the other chemical concentrations are reduced are the average WRF outlet concentrations for the year 2017 [23]. All the WRF inlet water is treated; i.e., the WRF has no waste stream. The implemented equations for $f_{transfer}$ WRF are as follows:

$$W_{\underset{OUT}{WRF}} = W_{\underset{IN}{WRF}} \tag{30}$$

$$PPM_{cal\underset{OUT}{WRF}} = 90.6 \tag{31}$$

$$PPM_{mag\underset{OUT}{WRF}} = 32.1 \tag{32}$$

$$PPM_{sod\underset{OUT}{WRF}} = PPM_{sod\underset{IN}{WRF}} \tag{33}$$

$$PPM_{alk\underset{OUT}{WRF}} = 32.3 \tag{34}$$

$$PPM_{cl^-\underset{OUT}{WRF}} = PPM_{cl^-\underset{IN}{WRF}} \tag{35}$$

$$PPM_{sul\underset{OUT}{WRF}} = 223.0 \tag{36}$$

3.4 Economics

This section details the “NPV PreP” and “NPV” modules in Figure 4. These modules compute all the cash flows considered in the economics analysis and compute the different economic figures of merit.

The economic analysis considers all relevant cash flows (revenue and expenses) for RO2 to compute its NPV and IRR. For PVGS/APS, on the other hand, differential NPVs are calculated (between CASE 0 and CASE 1). That means only cash flows that change between CASE 0 and CASE 1 are investigated. The analysis assumes that the following values are not changing between the different cases:

- F_{WRF}
- $CAPEX_{WRF}$
- NPP_{Variable}
- NPP_{fixed}

Furthermore, the effect of the electric load of the RO facilities on the grid (i.e., the increase of the baseload in the APS service region and the associated change in revenue from electricity sales for APS) is not considered in this study. The effect of additional (variable) load in the APS region was studied in detail in the 2018 INL report [1]; it was concluded that the opportunity to absorb negative prices at the electricity trading hub by simply adding baseload (on the order of RO1 and RO2 capacities) is negligible. The following sections detail the two scenarios, the associated cash flows and the potable water-market model used.

3.4.1 APS/PVGS and RO2 are Two Different Economic Entities

The first scenario considers APS and the owner/operator of the regional RO as two separate economic and business entities:

For APS: APS's goal is to cover the difference in cooling water acquisition and treatment cost. These are mainly the cost of the onsite RO and the change in effluent water need. APS will charge the LCOCT to the operator of RO2 in order to recover theses expenses. To evaluate the LCOCT, the water acquisition and treatment cost, in case no RO is built, needs to be evaluated first (CASE 0, see Figure 9). The difference in water acquisition and treatment between CASE 0 and CASE 1 will determine the LCOCT. This difference is actually the delta of the complete NPV for APS including all discounted revenues and expenses, but to evaluate the delta only cash flows that change between CASE 0 and CASE 1 need to be considered.

The water cash flows for CASE 1 are shown in Figure 10. Since RO2 will send its concentrate to PVGS, the water needs for effluent and brackish water at PVGS will change between CASE 0 and CASE 1; consequently, the associated acquisition and treatment cash flows will change as well. It is worth recalling that in CASE 0 where no ROs are built, no concentrate is produced. The only concentrate produced is from RO2 in CASE 1. To compute the LCOCT, the PVGS water cash flows for the remainder of the plant lifetime are discounted to today's dollors using the APS discount rate; i.e., partial NPVs are computed for CASE 0 and CASE 1, subtracted, and the LCOCT is evaluated, as follows:

$$LCOCT = \frac{NPV_{Water}^{PVGS,CASE1} - NPV_{Water}^{PVGS,CASE0}}{Concentrate\ water\ volume} \tag{37}$$

Two scenarios on what the LCOCT offsets are investigated:

- The LCOCT offsets the RO1 capital investment. In addition, it offsets the water acquisition and water treatment cost for the concentrate compared to the Base Case (CASE 0). In this case, APS water acquisition and treatment cost are kept constant between CASE 0 and CASE 1, while all the cost of concentrate treatment are transferred to the regional RO.
- The LCOCT offsets the RO1 capital investment. In addition, it offsets only the cost of the concentrate treatment. In this case, PVGS benefits from lowering water acquisition cost by using the desalinated concentrate water are kept out from the analysis and therefore cost transfer. There is no cost to PVGS for desalination of the concentrate (that is charged to the regional RO), but it reduces the need of expensive effluent water.

For the Regional RO: The regional RO's goal is to maximize its profit; i.e., find the optimal size of RO2 that maximizes the economic figure of merit. The cash flows considered for RO2 are the water acquisition, RO plant CAPEX (including depreciation), Operation and Maintenance (O&M), and waste water treatment cost. For the potable water revenue cash flow, two scenarios are considered:

- Its assumed that the potable water price is not known. In this case, the LCOPW will be searched for assuming NPV=0 (profit in accordance with RO2's discount rate) for RO2.
- A potable water market model for demand and supply is developed. The water price is evaluated using this model and the NPV and the Internal Rate of Return (IRR) are computed for RO2.

3.4.2 Global Project Economics

The first scenario might provide separate information for PVGS as well as potential investors for the regional RO plant, but does not look at the problem in the most general way. The first scenario requires both PVGS and RO2 to have positive (or zero) NPVs. This implies that if RO2 is not profitable for a given LCOCT, the project will not be realized, although there may have been a LCOCT that pushes RO2 into the profitable region while still being beneficial to PVGS, compared to CASE 0. This second scenario suggests finding the global NPV and considering both RO2 and APS as one economic entity. It is worth noting that although RO2 and APS are considered one economic entity in this case, they can still be two different business entities. Theory says that if the difference in NPV between CASE 0 and the global NPV for CASE 1 is positive, then this difference can be split between the two business entities to make both of them more profitable than CASE 0. Figure 11 shows the cash flows and water flows, considering RO2 and APS as one economic entity.

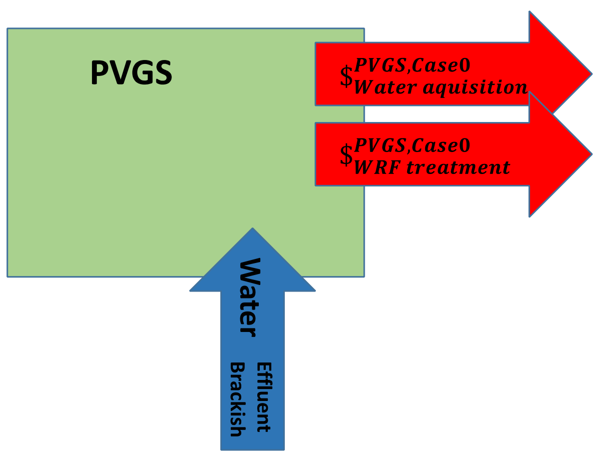


Figure 9. Cash and water flows at APS/PVGS for CASE 0, no RO is built.

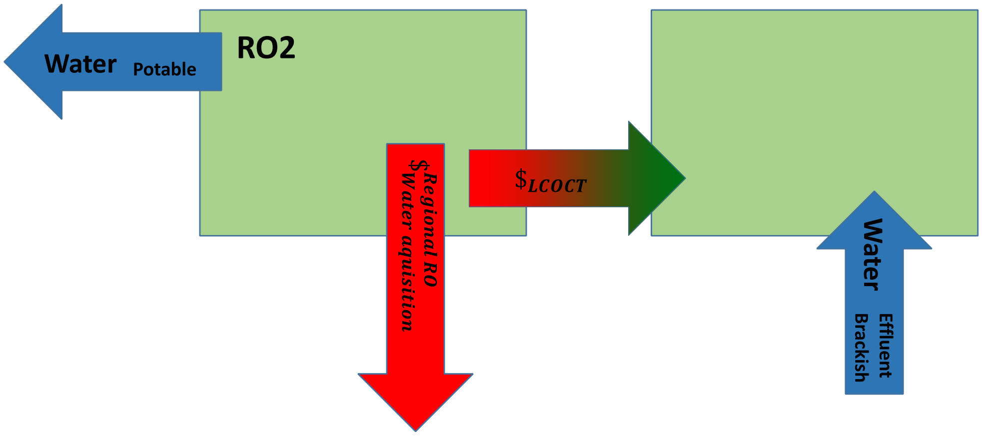


Figure 10. RO2 and APS separate entities: Cash and water flows at APS/PVGS and RO2 for CASE 1, RO1 and RO2 are both built.

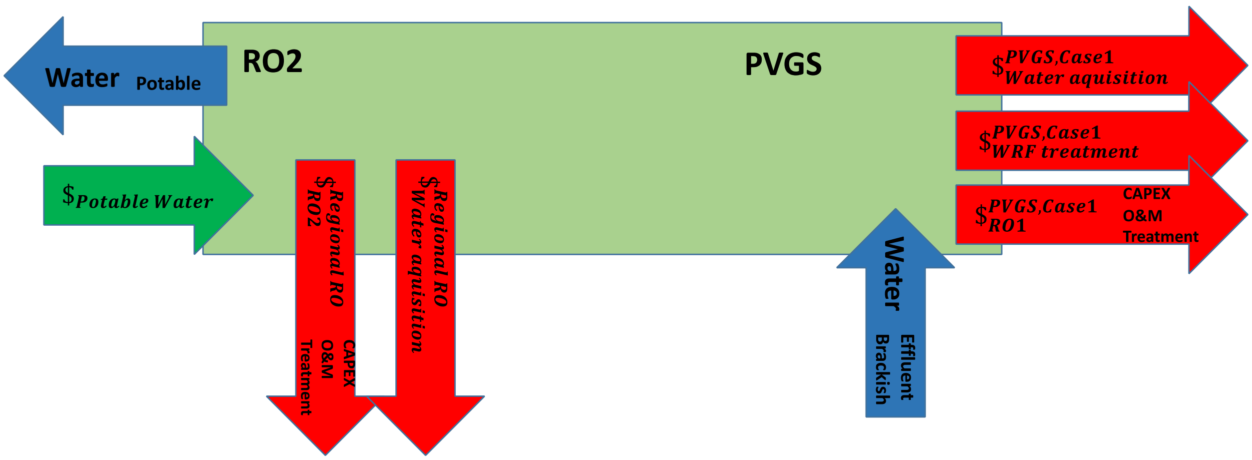


Figure 11. RO2 and APS form one economic entity (they can still be two business entities): Cash and water flows at APS/PVGS and RO2 for CASE 1, RO1 and RO2 are both built.

3.4.3 Cash Flows

3.4.3.1 CASE 0

To evaluate CASE 0, we try to isolate the cash flow, or better, the part that could be affected by the water supply strategy, which is seen by APS as the owner of 29.1% ($PowAPS\%$) of PVGS. Considering the 29.1% ownership of the PVGS by APS, we should consider 29.1% of the cooling-water-related expenses ($NPV^0_{\substack{Water\\APS}}$).

We assume that

$$NPV^0_{APS} = PowAPS\% \cdot NPV^0_{\substack{Water\\PV}} \tag{38}$$

and

$$NPV^0_{\substack{Water\\PV}} = NPV_{CW^0} + NPV_{CVE^0} \tag{39}$$

where:

- NPV_{CW^0} Partial NPV from water acquisition
- NPV_{CVE^0} Partial NPV from annual water treatment costs.

The partial NPV from water acquisition (NPV_{CW^0}) is computed as follows:

$$NPV_{CW^0} = \sum_{j=1}^{J} \frac{(1-Tax)\left(-CW_{j,eff}^0 - CW_{j,Br}^0\right)}{(1+WACC_{APS})^j} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,PumpWRSS}^0 - CE_{j,PumpWRSS}^0 - CF_{j,PumpWRSS}^0\right)}{(1+WACC_{APS})^j} \right\} - CAPEX_{PumpWRSS}^0 C_{PumpWRSS}^0 + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{PumpWRSS}^0 C_{PumpWRSS}^0\right)}{(1+WACC_{APS})^j} \right\}, \quad (40)$$

where,

For the water acquisition cost:

- $CW_{j,eff}^0$ Total annual costs from effluent water acquisition (see below).
- $CW_{j,Br}^0$ Annual costs from brackish water acquisition. This is $CW_{j,Br}^0 = \sum_i^{12} W_{Br,i} \cdot P_{Br}$.

For the brackish water pump (direct injection into the WRSS):

- $CV_{j,PumpWRSS}^0$ Brackish water pump annual costs from variable sources (excluding electricity).
- $CF_{j,PumpWRSS}^0$ Brackish water pump annual costs from fixed sources. $CV_{j,PumpWRSS}^0 + CF_{j,PumpWRSS}^0$ is assumed to be $2000/month independent of the pump size.
- $CE_{j,PumpWRSS}^0$ Brackish water pump annual costs from electricity consumption. The amount of electricity used by the brackish water pump ($E_{j,PumpWRSS}^0$) is proportional to the reference that pumping 400 AF needs 136500 kWh of power. The cost is then computed by $CE_{j,PumpWRSS}^0 = E_{j,PumpWRSS}^0 \cdot P_{E,W}$. Note that the pump is considered PVGS house load and consequently the wholesale price of electricity is applied ($P_{E,W}$).
- CAPEX The capital expenditure (i.e., the overnight building cost for the brackish water pumps for RO2) is expressed as product of $CAPEX_{PumpWRSS}^0 C_{PumpWRSS}^0$; i.e., [$/(kg/s)]*[kg/s].
- Depreciation Yearly depreciation of the capital expenditure expressed as depreciation coefficient D_j for each year times the capital cost.

For the effluent water, the total annual cost ($CW_{j,eff}^0$) is computed as follows:

$$CW_{j,eff}^0 = \sum_{i=1}^{12} \left(P_{j,eff}(W_{i,eff})\right) + Penalty_j\left(W_{j,eff}^0\right) \quad (41)$$

where:

- $P_{j,eff}(W_{i,eff})$ Monthly effluent water price as a function of the amount of effluent water bought by month [24]. This function includes multiple tiers; i.e., the first x acre feet have a certain price [$/AF], then the next y acre feet have a different price, etc. In addition, the price differs from year to year.
- $Penalty_j\left(W_{j,eff}^0\right)$ Yearly penalty for non-usage [24]. If at the end of the year, there is less water bought than contracted, a penalty for that "non-used" amount has to be played. The penalty is 20% of the average cost over the different tiers for that year. It is assumed that the contracted amount of water is 80000 AF/yr, minus the planned amount of brackish water and concentrate bought, as follows:

$$Penalty_j = \left[\left(80000 - \sum_{i=1}^{12}\left(W_{i,BrWRSS}\right) - \sum_{i=1}^{12}\left(W_{i,_{Waste}^{RO2}}\right)\right) - \sum_{i=1}^{12}\left(W_{i,eff}\right)\right] \cdot 0.2 \cdot avg(P_{j,eff,tiers}) \quad (42)$$

Next, the partial NPV from annual water treatment costs is computed as

$$NPV_{CVE^0} = \sum_{j=1}^{J} \frac{(1-Tax)}{(1+WACC_{PV})^j}\left\{-CV_j^0 - CE_j^0\right\}, \quad (43)$$

where the annual variable and fixed costs that come from water treatment (CV_j^0) for CASE 0 are only incurred by the WRF, as follows:

$$CV_j^0 = \sum_{i=1}^{12}\left(V_{WRF}(W_{i,_{IN}^{WRF}}, \overrightarrow{PPM}_{i,_{IN}^{WRF}})\right) \quad (44)$$

The variable cost function for the WRF is as follows [25]:

$$V_{WRF}(W, \overrightarrow{PPM}) = C_{CaO} \cdot D_{CaO} \cdot W + C_{Na2CO3} \cdot D_{Na2CO3} \cdot W + 6.719 \cdot 10^{-5} \cdot W + 1.366 \cdot 10^{6} + 5.851 \cdot 10^{-5} \cdot W \quad (45)$$

where

$$D_{CaO} = 0.00075\left[\frac{PPM_{mag}}{[PPM_{mag}]_o} + \frac{[PPM_{cal}]}{[PPM_{cal}]_o}\right] \quad (46)$$

$$D_{Na2CO3} = 0.0070\frac{D_{CaO}}{(D_{CaO})_o} \quad (47)$$

and

- C_{CaO} Cost of lime [$/lb]. (0.1 $/lb)
- C_{Na2CO3} Cost of soda ash [$/lb]. (0.17 $/lb)
- D_{CaO} Dosage of lime [lb/gal]
- $(D_{CaO})_o$ Average lime dosage [lb/gal] (0.0015 lb/gal)
- D_{Na2CO3} Dosage of soda ash [lb/gal]
- PPM_{mag} Magnesium concentration [ppm]
- $[PPM_{mag}]_o$ Average magnesium concentration [ppm] (142.1 ppm)
- PPM_{cal} Calcium concentration [ppm]
- $[PPM_{cal}]_o$ Average Calcium concentration [ppm] (187.5 ppm)
- $1.366 \cdot 10^6$ Fixed cost for one month [$].

The cost function V_{WRF} assumes the following:

- Principal chemical costs are for lime (CaO) and Soda Ash (Na_2CO_3) addition. Relatively lower chemical cost components (CO_2, Acid, Hypochlorite, and Polyfloc) are assumed independent of hardness and are lumped together as a residual cost that is a function of volume treated.
- Ca and Mg are the principal constituents for treatment. SiO_2 and PO_4 do not drive the lime and ash dosage.
- Chemical usage is baselined to the average dosage over the year 2017.
- Chemical unit costs ($/$lb_m$) are based on average 2017 values.
- Manpower, contract services and labor, and maintenance materials are assumed a fixed cost and are based on 2017 actuals for WRF.

The annual electricity costs that come from water treatment (CE_j^0) for CASE 0 are only incurred by the WRF. Note that the WRF is considered PVGS house-load and, therefore, the wholesale price of electricity ($P_{E,W}$) is considered, as follows:

$$CE_j^0 = \sum_{i=1}^{12} \left(E_{WRF}(W_{i,\underset{IN}{WRF}}) \cdot P_{E,W} \right) \quad (48)$$

The electricity consumption function for the WRF is as follows [25]:

$$E_{WRF}(W) = 714 + 1.8 \cdot 10^{-6} \cdot W \quad (49)$$

The electricity consumption function E_{WRF} assumes the following:

- Power costs are based on offsite demands (Hassayampa Pump Station (HPS) and cathodic protection) and WRF onsite demands (house loads).
- The onsite WRF power load is estimated to be 2.5 times the HPS loads at normal operating conditions with a baseload demand of 20% (lighting, etc.).

3.4.3.2 CASE 1

According to the discussion above, different scenarios are investigated for CASE 1.

APS/PV and RO2 Are Separate Economic Entities

As described above, to get separate information that could be used for decision making for APS and the owner of RO2, separate economic figures of merit have been computed. In this case, the cost for the concentrate treatment for APS has to be evaluated; i.e., the LCOCT. The LCOCT is searched so that the partial NPV (at APS) for CASE 1 equals the NPV at APS for CASE 0, i.e., as follows:

$$NPV_{APS}^0 = NPV_{APS}^1(LCOCT) \quad (50)$$

There are two options considered to what the LCOCT will offset. The first option considers that the LCOCT offsets all costs incurred with the concentrate treatment for APS and in addition also offsets the savings in water acquisition cost. The involved cash flows for this first option ($LCOCT^{option1}$) are as presented in Eq. 51.

$$NPV_{APS}^0 = PowAPS\% \cdot \left(\sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,WRF}^1 - CE_{j,WRF}^1\right)}{(1+WACC_{APS})^j} \right\} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CW_{j,Br}^1 - CW_{j,eff}^1\right)}{(1+WACC_{APS})^j} \right\} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,PumpWRSS}^1 - CE_{j,PumpWRSS}^1 - CF_{j,PumpWRSS}^1\right)}{(1+WACC_{APS})^j} \right\} - CAPEX_{PumpWRSS}^1 C_{PumpWRSS}^1 + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{PumpWRSS}^1 C_{PumpWRSS}^1\right)}{(1+WACC_{APS})^j} \right\} \right) + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,RO1}^1 - CE_{j,RO1}^1 - CF_{j,RO1}^1\right)}{(1+WACC_{APS})^j} \right\} + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{RO1}^1 C_{RO1}^1\right)}{(1+WACC_{APS})^j} \right\} - CAPEX_{RO1}^1 C_{RO1}^1 + \sum_{j=1}^{J} \left\{ \frac{(1-Tax) W_{\underset{Waste}{RO2},j} \cdot LCOCT^{option1}}{(1+WACC_{APS})^j} \right\} \quad (51)$$

where,

For the WRF:

- $CV_{j,WRF}^{1}$ WRF annual costs from variable sources (excluded electricity and water). This quantity is computed the same way as for CASE 0 (see Eq. 44).
- $CE_{j,WRF}^{1}$ WRF annual costs from electricity consumption. This quantity is computed the same way as for CASE 0 (see Eq. 48).

Water acquisition cost:

- $CW_{j,eff}^{1}$ Total annual costs from effluent water acquisition. This quantity is computed the same way as for CASE 0 (see Eq. 41).
- $CW_{j,Br}^{1}$ Total annual costs from brackish water acquisition. This is $CW_{j,Br}^{1} = \sum_{i}^{12} W_{i,Br} \cdot P_{Br}$.

For the brackish water pump (direct injection into the WRSS):

- $CV_{j,PumpWRSS}^{1}$ Brackish water pump annual costs from variable sources (excluded electricity).
- $CF_{j,PumpWRSS}^{1}$ Brackish water pump annual costs from fixed sources. $CV_{j,PumpWRSS}^{1} + CF_{j,PumpWRSS}^{1}$ is assumed to be 2000 $/month independent of the pump size.
- $CE_{j,PumpWRSS}^{1}$ Brackish water pump annual costs from electricity consumption. The amount of electricity used by the brackish water pump ($E_{j,PumpWRSS}^{1}$) is proportional to the reference that pumping 400 AF needs 136500 kWh of power. The cost is then computed by $CE_{j,PumpWRSS}^{1} = E_{j,PumpWRSS}^{1} \cdot P_{E,W}$. Note that the pump is considered PVGS house load and consequently the wholesale price of electricity is applied ($P_{E,W}$).
- CAPEX The capital expenditure (i.e., the overnight building cost for the brackish water pumps) for RO2 is expressed as product of $CAPEX_{PumpWRSS}^{1} C_{PumpWRSS}^{1}$;i.e., [$/(kg/s)]*[kg/s].
- Depreciation Yearly depreciation of the capital expenditure expressed as depreciation coefficient D_j for each year times the capital cost.

For the RO1:

- $CV_{j,RO1}^{1}$ RO1 annual costs from variable sources (excluded electricity and water).
- $CF_{j,RO1}^{1}$ RO1 annual costs from fixed sources. $CV_{j,RO1}^{1} + CF_{j,RO1}^{1}$ is assumed to be 1% of the CAPEX.
- $CE_{j,RO1}^{1}$ RO1 annual costs from electricity consumption. The amount of electricity used by the RO1 ($E_{j,RO1}^{1}$) is provided by the RO1 model (see Section 3.3.2). The cost is then computed by $CE_{j,RO1}^{1} = E_{j,RO1}^{1} \cdot P_{E,W}$. Note that RO1 is considered PVGS house load and consequently the wholesale price of electricity is applied ($P_{E,W}$).
- CAPEX The capital expenditure (i.e., the overnight building cost for RO1) expressed as product of $CAPEX_{RO1}^{1} C_{RO1}^{1}$; i.e., [$/(kg/s)]*[kg/s].
- Depreciation Yearly depreciation of the capital expenditure expressed as depreciation coefficient D_j for each year times the capital cost.

For the concentrate treatment cost:

- $W_{\substack{RO2 \\ Waste},j} \cdot LCOCT^{option1}$ The amount of concentrate from RO2 times the LCOCT. The LCOCT is the quantity the equation is solved for.

The second option, on the other hand, is that the LCOCT offsets all costs incurred with the concentrate treatment at APS as in the first case, but does not offset (i.e., is not lowered by) the savings in water acquisition cost at APS. It is worth noting that NPV_{APS}^{0} in this case should also not include the cost of effluent water acquisition, i.e. $CW_{j,eff}^{0} = 0$ in Eq. 40. The desalinated concentrate at PVGS will reduce the need to buy expensive effluent water. The involved cash flows for this second option ($LCOCT^{option2}$) are (all symbols used are already explained in the description of Eq. 51) as follows:

$$NPV_{APS}^{0} = PowAPS\% \cdot \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(-CV_{j,WRF}^{1}-CE_{j,WRF}^{1}\right)}{(1+WACC_{APS})^{j}}\right\} + \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(-CV_{j,RO1}^{1}-CE_{j,RO1}^{1}-CF_{j,RO1}^{1}\right)}{(1+WACC_{APS})^{j}}\right\} + \sum_{j=1}^{J}\left\{\frac{Tax\left(D_{j}CAPEX_{RO1}^{1}C_{RO1}^{1}\right)}{(1+WACC_{APS})^{j}}\right\} - CAPEX_{RO1}^{1}C_{RO1}^{1} + \sum_{j=1}^{J}\left\{\frac{(1-Tax)W_{\substack{RO2\\Waste},j}\cdot LCOCT^{option2}}{(1+WACC_{APS})^{j}}\right\} \quad (52)$$

Once the $LCOCT$ is determined, the economic figures of merit for the regional RO (RO2) can be evaluated. As for the cash flows for APS, two options are investigated for RO2 as well. The first option is to find the LCOPW; i.e., the water cost that leads to an NPV=0 or RO2. The associated cash flows are as follows:

$$NPV_{RO2}^{1} = 0 = \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(-CV_{j,RO2}^{1}-CE_{j,RO2}^{1}-CF_{j,RO2}^{1}\right)}{(1+WACC_{RO2})^{j}}\right\} + \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(-CV_{j,PumpRO2}^{1}-CE_{j,PumpRO2}^{1}-CF_{j,PumpRO2}^{1}\right)}{(1+WACC_{RO2})^{j}}\right\} + \sum_{j=1}^{J}\left\{\frac{Tax\left(D_{j}CAPEX_{RO2}^{1}C_{RO2}^{1}+D_{j}CAPEX_{PumpRO2}^{1}C_{PumpRO2}^{1}\right)}{(1+WACC_{RO2})^{j}}\right\} - CAPEX_{RO2}^{1}C_{RO2}^{1} - CAPEX_{PumpRO2}^{1}C_{PumpRO2}^{1} + \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(-W_{\substack{RO2\\Waste},j}\cdot LCOCT^{optionX}\right)}{(1+WACC_{RO2})^{j}}\right\} + \sum_{j=1}^{J}\left\{\frac{(1-Tax)\left(W_{\substack{RO2\\OUT},j}\cdot LCOPW\right)}{(1+WACC_{RO2})^{j}}\right\} \quad (53)$$

where,

For RO2:

- $CV_{j,RO2}^{1}$ RO2 annual costs from variable sources (excluded electricity and water).
- $CF_{j,RO2}^{1}$ RO2 annual costs from fixed sources. $CV_{j,RO2}^{1} + CF_{j,RO2}^{1}$ is assumed to be 1% of the CAPEX.
- $CE_{j,RO2}^{1}$ RO2 annual costs from electricity consumption. The amount of electricity used by the RO2 ($E_{j,RO2}^{1}$) is provided by the RO2 model (see Section 3.3.2). The cost is then computed by $CE_{j,RO2}^{1} = E_{j,RO2}^{1} \cdot P_{E,R}$. Note that RO2 is not considered PVGS house load and consequently the retail price of electricity is applied ($P_{E,R}$).
- CAPEX The capital expenditure (i.e., the overnight building cost for RO2) expressed as product of $CAPEX_{RO2}^{1}C_{RO2}^{1}$; i.e., [$/(kg/s)]*[kg/s].

- Depreciation Yearly depreciation of the capital expenditure expressed as depreciation coefficient D_j for each year times the capital cost.

For the brackish water pump for RO2:

- $CV^1_{j,PumpRO2}$ Brackish water pump annual costs from variable sources (excluded electricity).
- $CF^1_{j,PumpRO2}$ Brackish water pump annual costs from fixed sources. $CV^1_{j,PumpRO2} + CF^1_{j,PumpRO2}$ is assumed to be 2000 $/month independent of the pump size.
- $CE^1_{j,PumpRO2}$ Brackish water pump annual costs from electricity consumption. The amount of electricity used by the brackish water pump ($E^1_{j,PumpRO2}$) is proportional to the reference that pumping 400 AF needs 136500 kWh of power. The cost is then computed by $CE^1_{j,PumpRO2} = E^1_{j,PumpR02} \cdot P_{E,R}$. Note that the pump is not considered PVGS house load and consequently the retail price of electricity is applied ($P_{E,R}$).
- CAPEX The capital expenditure (i.e., the overnight building cost for the brackish water pumps for RO2) is expressed as product of $CAPEX^1_{PumpRO2} C^1_{PumpRO2}$; i.e., [$/(kg/s)]*[kg/s].
- Depreciation Yearly depreciation of the capital expenditure expressed as depreciation coefficient D_j for each year times the capital cost.

For the concentrate treatment cost:

- $W_{\substack{RO2\\Waste},j} \cdot LCOCT^{optionX}$ The cost to RO2 for concentrate treatment. The LCOCT is the one found for the desired option (see Eq. 51 and 52 above).

Revenue from potable water sales:

- $W_{\substack{RO2\\OUT},j} \cdot LCOPW$ The revenue from potable water sales that bring the NPV to zero. The equation is solved for LCOPW.

Another option is to evaluate the NPV and the IRR using a water price from a water marked model (see Section 3.5) instead of finding the LCOPW. The cash flows involved are the same as for the option to find the LCOPW, (see Eq. 53).

Global Project Economics

In this case, the difference of the partial NPVs for CASE 0 and CASE 1 is computed, as follows:

$$\Delta NPV^{CASE1/CASE0}_{APS/RO2} = NPV^1_{APS/RO2} - NPV^0_{APS} \tag{54}$$

As mentioned, if this difference is positive, the overall project is economically viable and the profit can be split between the participants so that everybody's NPV is higher compared to the case when the project is not realized. The cashflows for the combined NPV for APS and RO2 in CASE 1 are

$$NPV_{APS/RO2}^{1} = PowAPS\% \cdot \left(\sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,WRF}^{1} - CE_{j,WRF}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CW_{j,Br}^{1} - CW_{j,eff}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,PumpWRSS}^{1} - CE_{j,PumpWRSS}^{1} - CF_{j,PumpWRSS}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} - CAPEX_{PumpWRSS}^{1} C_{PumpWRSS}^{1} + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{PumpWRSS}^{1} C_{PumpWRSS}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} \right) + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,RO1}^{1} - CE_{j,RO1}^{1} - CF_{j,RO1}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{RO1}^{1} C_{RO1}^{1}\right)}{(1+WACC_{APS})^{j}} \right\} - CAPEX_{RO1}^{1} C_{RO1}^{1} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,RO2}^{1} - CE_{j,RO2}^{1} - CF_{j,RO2}^{1}\right)}{(1+WACC_{RO2})^{j}} \right\} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(-CV_{j,PumpRO2}^{1} - CE_{j,PumpRO2}^{1} - CF_{j,PumpRO2}^{1}\right)}{(1+WACC_{RO2})^{j}} \right\} + \sum_{j=1}^{J} \left\{ \frac{Tax\left(D_j CAPEX_{RO2}^{1} C_{RO2}^{1} + D_j CAPEX_{PumpRO2}^{1} C_{PumpRO2}^{1}\right)}{(1+WACC_{RO2})^{j}} \right\} - CAPEX_{RO2}^{1} C_{RO2}^{1} - CAPEX_{PumpRO2}^{1} C_{PumpRO2}^{1} + \sum_{j=1}^{J} \left\{ \frac{(1-Tax)\left(W_{\substack{RO2\\OUT'}j} \cdot P_{Water}\right)}{(1+WACC_{RO2})^{j}} \right\} \quad (55)$$

Where all symbols are already explained in the description of Eq. 51 and Eq.53, except

Revenue from potable water sales:

There are two options for the potable water revenue ($W_{\substack{RO2\\OUT'}j} \cdot P_{Water}$):

- Find the LCOPW, i.e. solve Eq. 55 for water price ($P_{Water} = LCOPW$) so that $\Delta NPV_{APS/RO2}^{CASE1/CASE0} = 0$.
- Find $\Delta NPV_{APS/RO2}^{CASE1/CASE0}$ using the water price model described later in Section 3.5 for P_{Water}.

3.5 Potable Water-Market Model for the Phoenix West Valley Region

The purpose of this section is to describe the water-market model used to represent the cities in the Phoenix west valley. Such a model enables one to project the quantity of potable water demanded over time, as well as the price municipal consumers are willing to pay. To describe the model requires a brief discussion of the underlying economic theory, followed by a description of the econometric method applied to estimate model parameters. Theory and application then provide a framework for projecting water demand by municipality over time. The cities reflected in the model are those in geographic proximity to the PVGS RO facility. They include the cities of Buckeye, Goodyear, Tolleson, and Avondale (see Figure 1).

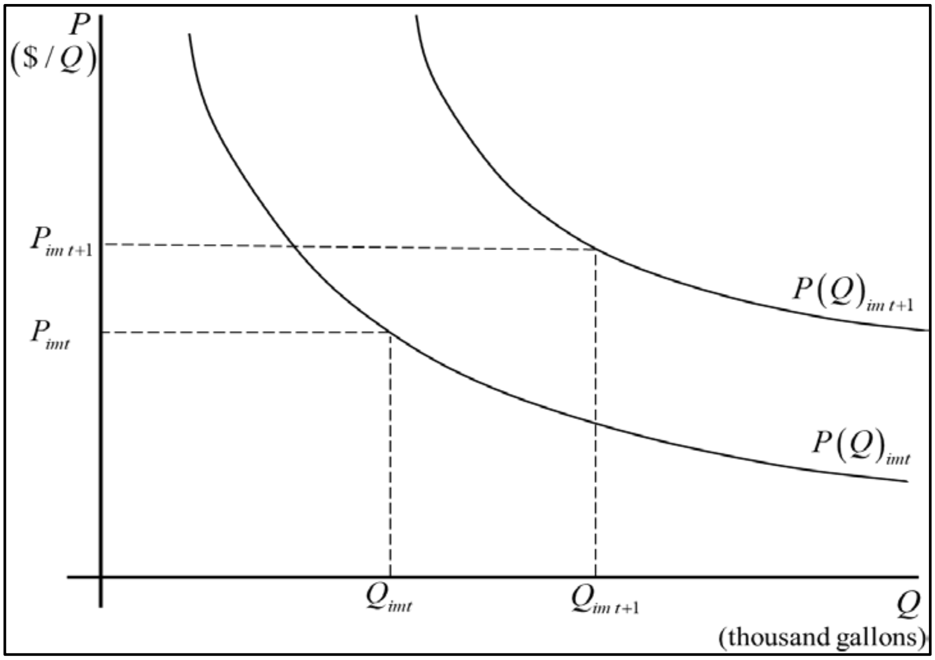


Figure 12. Conceptual water demand model showing water demand (Q) as a function of price (P).

Figure 12 illustrates the theory underlying the basis of analysis. The two curves in the figure, labeled $P(Q)$, represent two different water demand curves. The subscript notation *imt* represents the model applied to municipality *i*, in month *m¸* at year *t* in the projection. The demand curve maps out the relationship between water prices and the quantity of water demanded. It allows one to project, for given price P_{imt}, the quantity of water demanded, Q_{imt}, in each municipality by month and year. The demand curve also indicates that for a given projected water quantity the projected price that residents in *i* might be willing to pay for water.

This model is used to generate a projection, so there is a need to know numerically how $P(Q)_{imt}$ shifts to $P(Q)_{im\,t+1}$, and all future time periods in the projection. The need also encompasses the shape of the demand curve. Generating these parameters entails the use of econometric estimation to measure the relationship between water demand and factors that drive it.

Section 3.5.1 describes the data underlying the estimation of these curves for each city. Then Section 3.5.2 describes the results of the water demand/cost econometric analysis, which includes the parameters that describe the shape of the curve and how it shifts. Section 3.5.3 illustrates how to use the water demand model for forecasting.

3.5.1 Data

Estimating the functional form of the demand equations shown above requires data on water prices, water consumption, and the population of the community for which the demand curve is estimated. Data for this analysis are found in two sources, the Arizona Department of Water Resources (ADWR), and the U.S. Census Bureau. A description of the data from each source follows.

Through the data center of the ADWR website, one can access an archive of imaged records on file with the Department [26]. This archive contains numerous records, but one particular type contains useful information from which data for this analysis can be extracted. Annually, municipal water utilities file a report titled the *Annual Water Withdrawal and Use Report*. One item in the report provides information on water deliveries to consumer types by month in each year. The data are disaggregated across residential and non-residential users. Within residential, further disaggregation is that of single-family versus multi-family deliveries. In the non-residential category customer types include industrial, commercial, government, turf-related activities, and construction. From this set of information, for each city and spanning the years from 2010 to 2018, analysts extracted the water delivery data for single family, residential users. This was done for two reasons. First, single-family water use is the largest fraction of water deliveries. The second reason has to do with water prices. In order to estimate the demand function, consumption and price data are required. In the reports from ADWR, the residential water rates for single-family use are consistently and clearly indicated. Such is not the case for other customer types; thus, residential water demand is estimated based on single-family water data.

The model shown in Figure 12 shows the water price in units of dollars per thousand gallons. Extracting this rate for each city required calculation based on the data obtained from ADWR. In addition to data on water deliveries, the ADWR reports also include a water rate sheet for the year of the filed report. But the rates are not in units of dollars per thousand; the data instead are in price per block of water. That is, water rates are administered in an increasing block rate design, so the water rate differs based on the level of consumption. To find the water rate in units of dollars per thousand, *P*, listed in the figure, analysts computed a weighted average rate by weighting the water rate based on the volume of water in each block. The resulting weighted average has the interpretation of dollars per thousand gallons by month by community. Then the monetary units are normalized to 2015 dollars, using the *Consumer Price Index*, published by the U.S. Bureau of Labor Statistics [27].

From the U.S. Census Bureau report *Annual Estimate of the Resident Population,* spanning April 1, 2010, to July 1, 2018, analysts obtain the yearly estimate of population for the municipalities in the study [28]. This data from the Census list each of the cities in Arizona, so it is a useful data source for understanding growth in the region.

Table 6 provides the descriptive statistics of the variables derived from the data sources discussed here. The data are disaggregated by the municipalities in the analysis.

Table 6: Descriptive statistics of water demand variables.

City	Variable	Min	Max	Mean	St. Dev.	Units
Buckeye	consumption	51491	103050	72587	10877	thousand gallons
	water rate	2.02	4.37	3.11	0.86	dollars per thousand gallons
	Population	50396	76815	60279	7361	people
Goodyear	consumption	75777	177234	120616	24992	thousand gallons
	water rate	0.82	2.83	1.65	0.47	dollars per thousand gallons
	Population	65050	84035	73012	5789	people
Tolleson	consumption	7107	21304	12067	2883	thousand gallons
	water rate	1.12	3.04	2.34	0.45	dollars per thousand gallons
	Population	6524	7319	6958	266	people
Avondale	consumption	121008	289453	199581	41229	thousand gallons
	water rate	1.02	2.11	1.39	0.25	dollars per thousand gallons
	Population	75977	86265	80937	3125	people

3.5.2 Residential Water Demand

Table 7: Variables and notation in water demand model.

imt	Subscript denoting municipality *i* in month *m* in year *t*
Q_{imt}	Residential water demand in thousands of gallons
A_m	A constant parameter estimated with econometric analysis
P_{imt}	Residential water rate, and willingness to pay, in dollars per thousand gallons, in constant year 2015 dollars
N_{imt}	Population in the municipality in month *m* in year
α	Price elasticity of demand
η	Elasticity of population
r	Month-on-month growth rate in prices
n	Month-on-month growth rate in population
0	Subscript to indicate parameter value taken from data in year 2018

Table 7 introduces the needed nomenclature for the following equations. The functional form of the equations represented in Figure 12 is given as Eq. 56, which shows the quantity of water demanded as a function of a constant term, *A*, the water price, *P*, and the population of residents in the community, *N*. The parameters α and η are elasticities. They describe the responsiveness of demand to changes in price and population, respectively.

$$Q = AP^{\alpha} N^{\eta} \tag{56}$$

In order to estimate the parameters in Eq. 56, (*A*, α , and η), econometric analysis should be applied to the data in Table 6. Because the data are at the municipality level, by month, spanning 2010 to 2018, the data are said to be panel data. This means that each city represents a 'panel' wherein the data vary over time. The econometric specification needed to estimate a model based on panel data is either a random effects model (RE), or a fixed effects model (FE). One way to think about the differences between the RE and the FE is that in the FE model, the methodology explicitly controls for unobserved differences in the panels. For example, one municipality might have developed a culture of conservation that another city has not. If so, and if that culture was a statistically significant driver of behavior, then a FE model would capture the differences between the cities. On the other hand, a RE model randomizes the differences between the panels. Table 8 shows the results of both estimations. The analyst must then choose which is the preferred model. A statistical test called the Hausman test enables the analysts to determine which approach better fits the data. In this case, the Hausman test indicates that the RE model provides a better fit of the data. The coefficients in Table 8 are utilized to parameterize Eq. 56.

Table 8: Residential Water Demand Regression Results.

Dependent variable: log(consumption)				
	RE		FE	
log(water rate)	-0.133***	(0.032)	-0.034	(0.045)
log(population)	0.833***	(0.081)	0.504***	(0.134)
February	-0.046*	(0.025)	-0.049**	(0.025)
March	-0.051**	(0.025)	-0.050**	(0.025)
April	0.155***	(0.025)	0.156***	(0.025)
May	0.253***	(0.025)	0.244***	(0.025)
June	0.394***	(0.025)	0.382***	(0.025)
July	0.455***	(0.026)	0.437***	(0.026)
August	0.448***	(0.026)	0.428***	(0.026)
September	0.377***	(0.026)	0.358***	(0.026)
October	0.291***	(0.026)	0.275***	(0.026)
November	0.204***	(0.025)	0.192***	(0.025)
December	0.038	(0.025)	0.029	(0.025)
Constant	2.160**	(0.848)	$6.30^{***}_{Avondale}$	(0.036)
			$5.48^{***}_{Buckeye}$	(0.000)
			$5.85^{***}_{Goodyear}$	(0.098)
			$4.74^{***}_{Tolleson}$	(0.051)
Observations	428		428	
R2	0.767		0.760	
Adjusted R2	0.759		0.751	
F Statistic	1,359.463***		100.099***	
Note: *p<0.1; **p<0.05; ***p<0.01; (standard error)				

3.5.3 Forecasting Water Demand

Figure 12 shows different types of information that can be ascertained using the estimated water demand equation. Using a demand model, one can determine customers' willingness to pay (price) given a specific quantity. Similarly, given a specific price one can determine the quantity consumers will demand. This relationship is the basis for forecasting water demand and water prices using a demand model.

To determine projected water demand, rearrange Eq. 56 into the Eq. 57 format, then substitute in parameters to determine a projection of residential demand for water across months and years, by municipality. Parameters to populate the equation are in Table 9 and Table 10. These tables show the values of population and water prices for 2018, which can be taken as the initial values in the projection. They also show the growth rates and elasticities. Eq. 57 depends on the growth parameters *r* and *n*, which represent the growth in water rates and population, respectively.

$$Q_{imt} = A_m \left(P_{im0}[1+r]^t\right)_{imt}^{\alpha} \left(N_{im0}[1+n]^t\right)_{imt}^{\eta} \tag{57}$$

To determine projected price, Eq. 56 is converted Eq. 58. It projects residents' willingness to pay for water in each community across the projection time frame.

$$P_{imt} = \left[\frac{Q_{imt}}{A_m \left(N_{im0}[1+n]^t\right)_{imt}^{\eta}}\right]^{\frac{1}{\alpha}} \tag{58}$$

Table 9: Input Values by Month.

		Buckeye		Goodyear		Tolleson		Avondale	
	A_m	P_{m0}	N_{m0}	P_{m0}	N_{m0}	P_{m0}	N_{m0}	P_{m0}	N_{m0}
Jan	8.67	4.13	71461	2.00	81390	2.31	7276	1.53	85323
Feb	8.28	4.13	71945	2.00	81631	2.16	7280	1.60	85409
Mar	8.24	4.14	72429	2.25	81872	2.17	7284	1.56	85495
Apr	10.12	4.14	72913	2.12	82113	2.67	7288	1.72	85581
May	11.17	4.25	73397	2.33	82354	2.78	7292	1.90	85667
Jun	12.86	4.31	73881	2.72	82595	3.04	7296	2.07	85753
Jul	13.67	4.19	74370	2.56	82835	2.94	7299	1.96	85835
Aug	13.57	4.24	74859	2.83	83075	2.88	7303	2.11	85921
Sept	12.64	4.37	75348	2.56	83315	3.01	7307	2.07	86007
Oct	11.6	4.19	75837	2.33	83555	2.51	7311	1.74	86093
Nov	10.63	4.26	76326	2.52	83795	2.48	7315	1.77	86179
Dec	9.01	4.19	76815	2.03	84035	2.30	7319	1.63	86265

Table 10: Input values for system parameters.

	r	n	α	η
Buckeye	0.0974	0.0475		
Goodyear	0.1109	0.0296		
Tolleson	0.0766	0.0136		
Avondale	0.0536	0.0148		
All	0.0799	0.0295	-0.13	0.83

The data in the tables are attained from the data sources described in Section 3.5.1. Growth rates are calculated by municipality on a month-to-month basis, then averaged to get the yearly growth rate. The same method is applied to water prices to get the growth rate in water prices by city.

4. SIMULATIONS

This chapter presents the results of the economic analysis for the APS cases introduced in the previous chapters. First, the input data and assumptions are discussed. After that, in the second section of this chapter, the results of the analysis, including the sensitivity studies performed for selected inputs, are presented and discussed.

4.1 Input Data and Assumptions

As mentioned, this section presents the model inputs. The assumptions made in the physical modeling (water flows and chemical compositions), as well as in the cash flows, have already been discussed in Section 3. The inputs include the values presented in Table 1 (physics) as well as the economic parameters such as tax, inflation rate, etc., presented in Table 2. Inputs that have a corresponding sensitivity study performed are indicated with the "reference value" colored in red [23-36].

NumberOfYears	J	[years]	**27, 47**
PowAPSPercent	$PowAPS\%$	[%]	**29.1**
EL_wholesale_price	$P_{E,W}$	[$/MWh]	**30.0, 35.0, 40.0**
EL_RetWholeDiff	$P_{E,diff}$	[$/MWh]	**10.0**
	This is the difference between wholesale and retail price, $P_{E,R} = P_{E,W} + P_{E,diff}$		
Blowdown	$BlowD$	[%]	**4.0**
Maximum blowdown	MaxBD	[gpm]	**2200**
	This is the maximum of the sum of RO1 concentrate and PVGS cooling tower blowdown; $MaxBD = \max\left(W_{\substack{RO1\\Waste}} + W_{blowdown}\right)$		
PBrackish	P_{Br}	[$/AF]	**25.0**
PEffluent	P_{eff}	[$/AF]	The effluent water-price structure is a multi-tier structure where water becomes more expensive as more water is purchased. In addition, the water becomes more expensive from year to year.
W_brackishRO2	W_{Br}	[kg/month]	parametric from 100e6 (970 AF/yr) to 3e9 (29000 AF/yr). No variation during the year has been considered; i.e., the same amount of brackish water is purchased every month.
W_brackishWRRS	W_{Br}	[kg/month]	parametric from 0 (0 AF/yr) to 1.5e9 (15500 AF/yr). No variation during the year has been considered; i.e., the same amount of brackish water is purchased every month.
Chem_cal_brackish	$PPM_{Br,cal}$	[ppm]	**180.0**
Chem_mag_brackish	$PPM_{Br,mag}$	[ppm]	**80.0**
Chem_sod_brackish	$PPM_{Br,sod}$	[ppm]	**780.0**
Chem_alk_brackish	$PPM_{Br,alk}$	[ppm as $CaCO_3$]	**244.0**

Chem_clo_brackish	$PPM_{Br,clo}$	[ppm]	**799.0**
Chem_sul_brackish	$PPM_{Br,sul}$	[ppm as SO_4]	**1180.0**
CoolingPVGS[2]	W_{EvCool}	[kg/month]	**6.71e9, 6.20e9 7.10e9, 5.00e9, 8.17e9, 8.46e9, 8.73e9, 8.65e9, 7.99e9, 5.07e9, 7.02e9, 6.86e9**
CoolingRH[1]	W_{RH}	[kg/month]	**1.23e8, 1.53e8, 2.34e8, 1.01e8, 6.60e8, 5.22e8, 6.11e8, 5.19e8, 4.70e8, 1.74e8, 6.38e8, 2.77e8**
Chem_cal_eff[2]	$PPM_{eff,cal}$	[ppm as $CaCO_3$]	**194.0, 222.0, 175.3, 193.3, 181.2, 165.5, 187.0, 157.8, 198.8, 190.7, 188.5, 196.8**
Chem_mag_eff[2]	$PPM_{eff,mag}$	[ppm as $CaCO_3$]	**140.0, 154.0, 139.5, 135.7, 132.4, 139.3, 150.8, 141.8, 143.0, 139.3, 146.0, 142.8**
Chem_sod_eff[2]	$PPM_{eff,sod}$	[ppm]	**264.0, 250.0, 215.0, 250.0, 297.0, 293.5, 383.7, 258.0, 284.5, 229.3, 182.3, 244.5**
Chem_alk_eff[2]	$PPM_{eff,alk}$	[ppm as $CaCO_3$]	**163.0, 175.0, 169.3, 160.0, 154.4, 164.0, 161.0, 151.4, 153.5, 159.7, 169.5, 166.5**
Chem_clo_eff[2]	$PPM_{eff,clo}$	[ppm]	**301.0, 345.0, 292.5, 292.5, 359.0, 445.5, 477.0, 448.8, 471.0, 353.7, 168.0, 286.0**
Chem_sul_eff[2]	$PPM_{eff,sul}$	[ppm]	**215.0, 248.0, 186.5, 186.5, 167.0, 191.5, 185.8, 195.0, 177.8, 164.0, 159.0, 183.5**
DiscoutRate APS	$WACC_{PV} = WACC_{APS}$	[%]	**5, 10, 15**
DiscountRate RO2	$WACC_{RO2}$	[%]	**5, 10, 15**
Inflation	Inf	[%]	**3**
Tax	Tax	[%]	**21.0**
Depreciation	D_j	[%]	A 15-year MACRS accelerated depreciation table is used for the RO plants, while a 7-year MACRS is used for the brackish water pump.
CAPEX RO	$CAPEX_{ROx}$	[$/(kg/s)]	**64800.0**
CAPEX Pump	$CAPEX_{Pump}$	[$/(kg/s)]	**2,105.3**

[2] Note that these values are not a sensitivity study, but reflect the change during the year.

4.2 APS Case Simulations

This section presents the simulation results for the four APS scenarios (Case 0 and Case 1) using the input data in Section 4.1. First, the reference scenario is presented (as discussed in Section 4.2.1) followed by the sensitivity studies.

4.2.1 Scenario 1: Reference

The reference scenario uses information from Section 4.1 as a baseline. The reference parameters are indicated in red for convenience.

Two cases are run within each scenario. The first case (CASE 0) finds the optimal/maximum amount of brackish water that can be blended into the WRSS without the need of building an onsite RO at PVGS. This case represents the minimum cost-of-water acquisition (partial NPV) for APS without building any RO plants. As mentioned, the other cases studied that include ROs will be compared to this Base Case. The Base Case (CASE 0) is the same for all scenarios studied.

The second case (CASE 1) models a regional RO (RO2) and an on-site RO at PVGS (RO1). Ranges have been investigated for the independent variables (RO1 size, brackish water injected into the WRSS, and size of RO2). The goal is to satisfy the physical and economic boundary conditions for the modeled system and find the respective optimums.

4.2.1.1 CASE 0: Existing Palo Verde configuration – Maximum brackish water without supplemental RO treatment

Within the reference scenario, CASE 0 refers to the current PVGS plant design (tertiary treatment and evaporation pond capacity) and the maximum allowable brackish groundwater volume that may be introduced to offset the same volume of effluent without supplemental RO treatment. As discussed in Section 2.1 and shown in Figure 2, CASE 0 seeks to find the economically optimal amount of brackish water that can be input into Palo Verde's tertiary water system while maintaining the site water balance. The maximum volume of brackish groundwater that may be used is dependent upon maintaining circulating water system blowdown less than a predefined average limit that ensures acceptable long-term levels in the evaporation ponds, and that maintains the chemistry limits in the reservoirs below administrative values. The latter constraint ensures that the water supply for RPS is also within operational limits.

Physics

Figure 13 shows the chloride concentration in the reservoir as a function of brackish water input into WRSS. In addition, the blowdown is plotted against brackish input in Figure 14. Looking at both figures, one can see that:

- Considering only the first constraint (a), the blowdown limit for the evaporation ponds is 4.38e6 m^3/yr (2200 gpm, 3550 AF/yr) and a brackish input of approximately 3.6e7 m^3/yr (29000 AF/yr) will cause the cooling system to exceed that limit (see Figure 14) when there are no ROs in the system. The corresponding chloride concentration in the reservoir is ~550 ppm. It is worth recalling that all reported chloride concentrations are yearly time-averages, not maximums.
- Considering the second constraint (b), the chloride concentration operational target in the reservoir pond is 450 ppm. As one can see in Figure 13 the system reaches 450 ppm at 1.9e7 m^3/yr (15500 AF/yr). The chloride concentration is the more conservative constraint between the two. The red line in the figures indicates the 450 ppm chloride constraint.

- Although the blowdown is constant for chloride concentrations lower than 450 ppm, the blowdown increases slightly in Figure 14 when the brackish input is less than 1.9e7 m^3/yr (15500 AF/yr) (i.e., chloride concentration < 450 ppm; see Figure 13), because individual months have circulating water inlet chloride concentrations above 450 ppm. When the brackish water flow rate exceeds 1.9e7 m^3/yr (15500 AF/yr), the average yearly reservoir chloride concentration exceeds 450 ppm and results in an increase in blowdown. Consequently, the total volume of cooling water required by PVGS is increased. This trend is illustrated by the inflection point at 1.9e7 m^3/yr (15500 AF/yr).

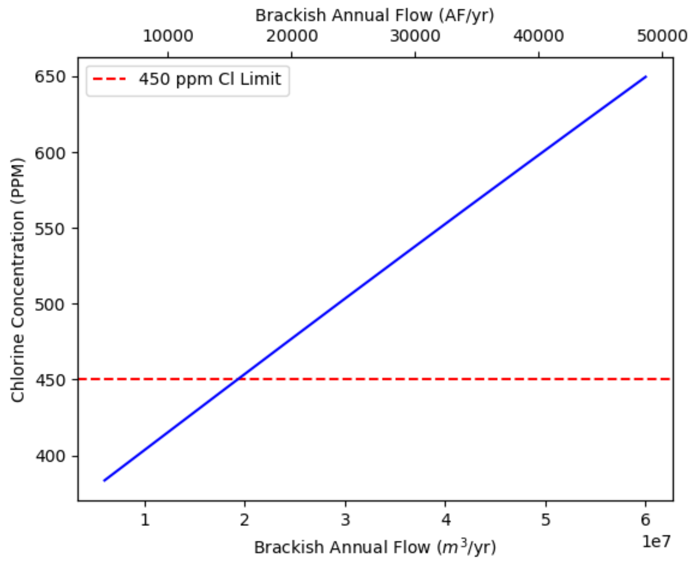


Figure 13. Chloride concentration at the PVGS cooling water reservoir vs brackish flow rate into the WRSS. Note the system reaches the 450 ppm constraint (red line) at 1.9e7 m^3/yr (15500 AF/yr).

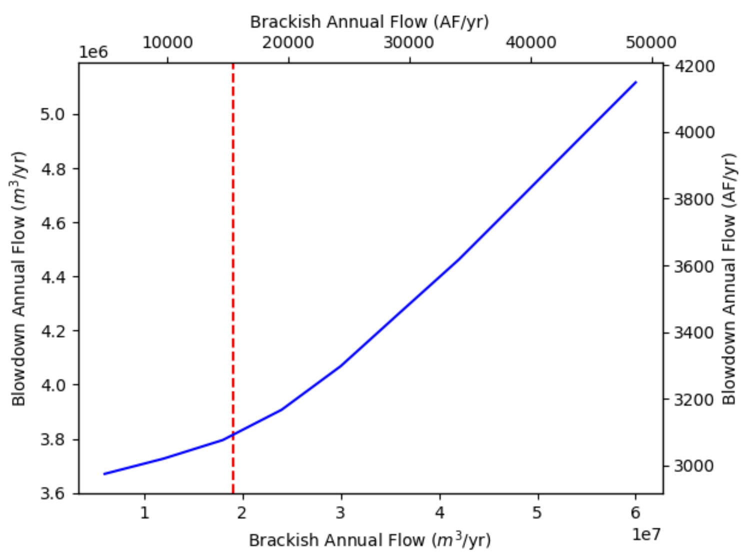


Figure 14. Cooling tower blowdown vs brackish flow rate into the WRSS. The red line represents the point at which the reservoir chlorides reach 450 ppm.

The Base Case, i.e. CASE 0 (where all subsequent cases with RO are compared) has been chosen to be the one with the more-restrictive constraint; i.e., the one where the average chloride concentration in the reservoir ponds is below 450 ppm. For information, the effluent usage is plotted against the brackish withdrawal in Figure 15. One can see that effluent need decreases as brackish water increases, even as the reservoir chloride concentration passes 450 ppm and more total water is required in the circulating water system. There is a slight change in slope when that happens, but it is too small to be visible in the figure.

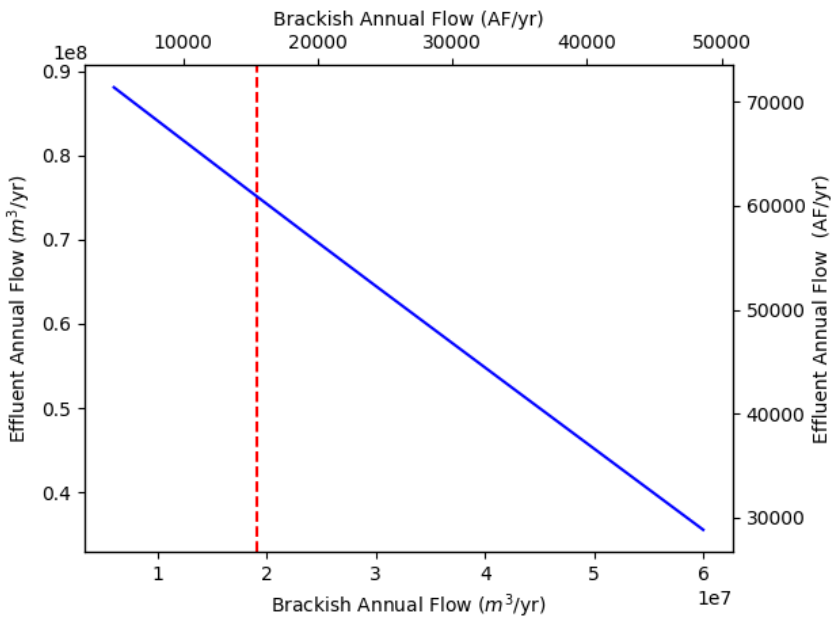


Figure 15. Annual effluent flow rate vs brackish flow rate into the WRSS. The red line represents the point at which the reservoir chlorides reach 450 ppm.

Economics

Looking at the economics of CASE 0, the partial NPV (just considering the cooling water acquisition) is plotted in Figure 16 versus brackish water input directly in WRSS. The NPV increases with brackish water inlet, meaning that it is economically advantageous to use as much brackish water as possible. Note that the magnitude of the NPV is not necessarily useful by itself. The NPV is negative because revenue is not calculated. The revenue portion of Palo Verde (the sale of electricity) will remain consistent throughout each case and scenario in this analysis and can thus be neglected in an analysis of the delta NPV between cases. When other inputs are adjusted, the NPV from CASE 1 can be matched to the NPV from CASE 0, ensuring that the adjusted inputs only offset the difference in water acquisition between CASE 0 and CASE 1. One can see that the partial NPV for the chosen reference (450 ppm chloride concentration in reservoir ponds, indicated by the red line in Figure 16) is ~ $ 94 million. This number should only be used when comparing to the NPV in CASE 1. Details for the cash flows considered (for one year) are shown in Table 11. For the effluent water cost, the range over the project life is indicated, since the effluent water cost will increase over time.

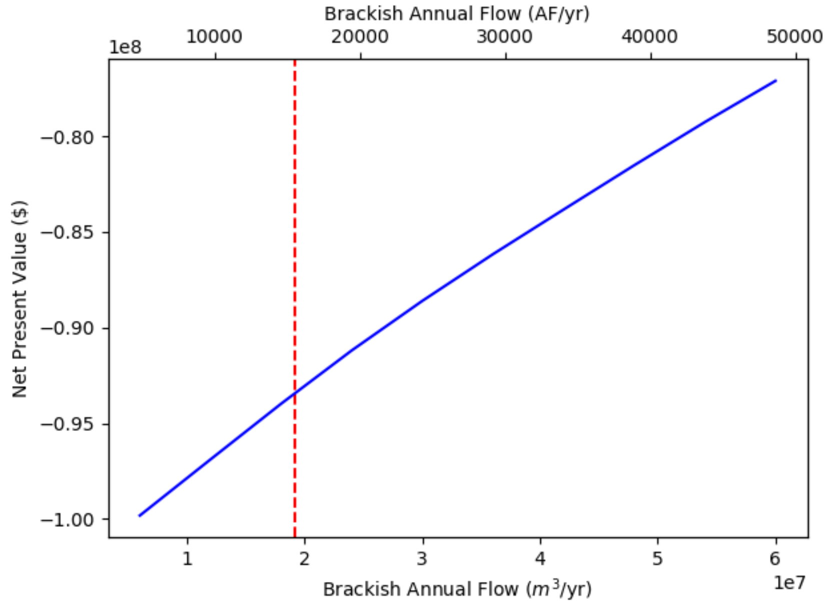


Figure 16. Partial NPV vs brackish flow rate into the WRSS. The red line represents the point at which the reservoir chlorides reach 450 ppm. Note that the NPV is negative because only cooling water acquisition and no revenue is taken into account.

Table 11: CASE 0 cash flows.

Cash Flow	Value for one year [million $]
WRF chemicals	25
WRF electricity	2
Effluent water	9 - 30
Brackish water (pumping)	0.5

4.2.1.2 Case 1: Regional and PV RO plants

The purpose of CASE 1 is to find the optimal physical and economic configuration for the regional RO and PVGS RO, as described in Section 2.2 and Figure 3. The model has three degrees of freedom:

- The amount of brackish water sent into the regional RO; i.e., RO2 size.
- The percentage of WRF outlet water treated by RO1 (slipstream designated as α); i.e., RO1 size.
- The amount of brackish water directly injected into the WRSS.

The amount of brackish water sent to RO2 sets the regional RO capacity. Alpha determines the size of the slipstream treated by RO1 and consequently sets the capacity of RO1. When building the ROs, it might be economically beneficial to inject more or less brackish water into the WRSS compared to CASE 0. It is worth noting that the NPV for different brackish water amounts in CASE 1 are always to be compared to the optimum NPV for CASE 0; i.e., the one using 1.9e7 m^3/yr (15500 AF/yr). A range of the three independent variables, shown in Table 12, was investigated.

Table 12: Scenario 1, CASE 1 Optimization Parameters.

Model parameter	Minimum	Maximum
Regional RO size	1.2e6 m^3/yr (973 AF/yr)	3.6e7 m^3/yr (29186 AF/yr)
Percentage of WRF outlet treated in PV RO (α)	0%	5%
Brackish water into WRSS	0	1.9e7 m^3/yr (15500 AF/yr)

Blowdown constraint

As for CASE 0, the main physical boundary conditions in this analysis are flow rate to the evaporation ponds, or overall blowdown and reservoir pond salinity. Let's first consider the blowdown constraint. The total waste sent to the evaporation pond from the RO and from the PV circulating water system cannot exceed 4.38e6 m^3/yr (2200 gpm, 3550 AF/yr). This flow rate is constrained by the size of evaporation ponds and the rate at which evaporation occurs. The sensitivities in capacity of RO2, α and brackish water into the WRSS seek to find points at which this condition is satisfied. Figure 17 shows the scenario sensitivities plotted against total blowdown. The pumped brackish water is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The maximum size of the regional RO is 1.4e7 m^3/yr (10990 AF/yr) for which the total blowdown (including regional RO concentrate treatment at PVGS either through increased blowdown or onsite RO treatment) remains under the evaporation pond limit. The highest feasible brackish input coincides with the smallest α for RO1, i.e. no RO1. Larger RO1s can handle less concentrate from the regional RO, because the larger RO1 waste stream quickly reaches the evaporation pond limit. This is due to the fact that the PV RO works around 80% efficiency, while the blowdown in the PV circulating water system is ~4%; i.e., the circulating water system has an equivalent efficiency of removing chlorides of ~96%. Thus, it is advantageous to send higher-salinity water to the cooling tower (instead of treating in an onsite RO), even if water consumption has to increase. This only considers the physics of the problem; the economics might change that statement depending on evaporation and RO capex and O&M costs.

Figure 18 and Figure 19 show a sensitivity to the volume of pumped brackish water. Each plot shows the total blowdown as a function of RO2 size. Curves in the plot are for different brackish water amounts injected into the WRSS. Two RO1 sizes have been investigated (0.0% and 5% split stream). One can see that, without building the RO1 (0.0% case) and not injecting brackish water into the WRSS, the possible size of RO2 respecting the blowdown limit is maximized (~ 2.8e7 m^3/yr (23000 AF/yr)). On the other hand, in building a RO1 that treats 5% of the split stream, the blowdown limit is violated even if no brackish water is injected into the WRSS.

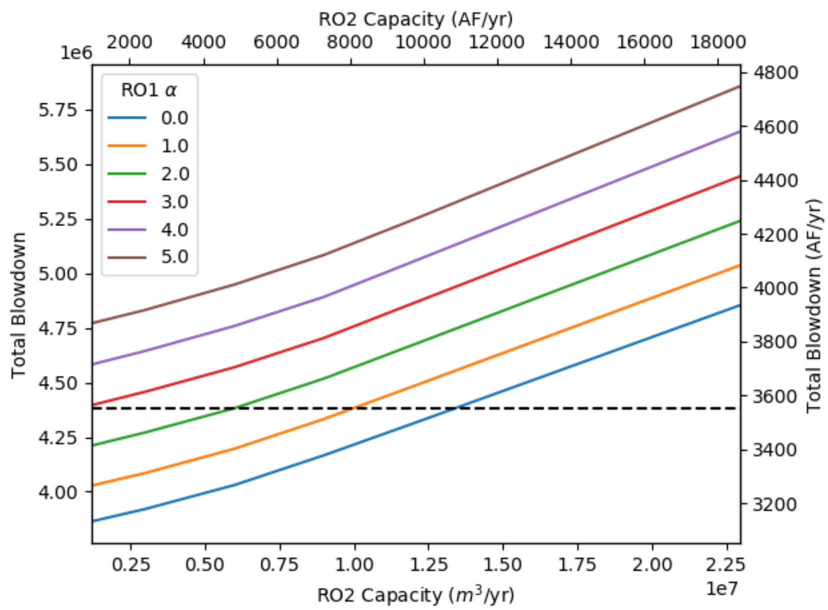


Figure 17. Total blowdown vs regional RO size as a function of α for RO1 (different color lines). The pumped brackish water is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The black line indicates the maximum flow rate that the current evaporation ponds can handle.

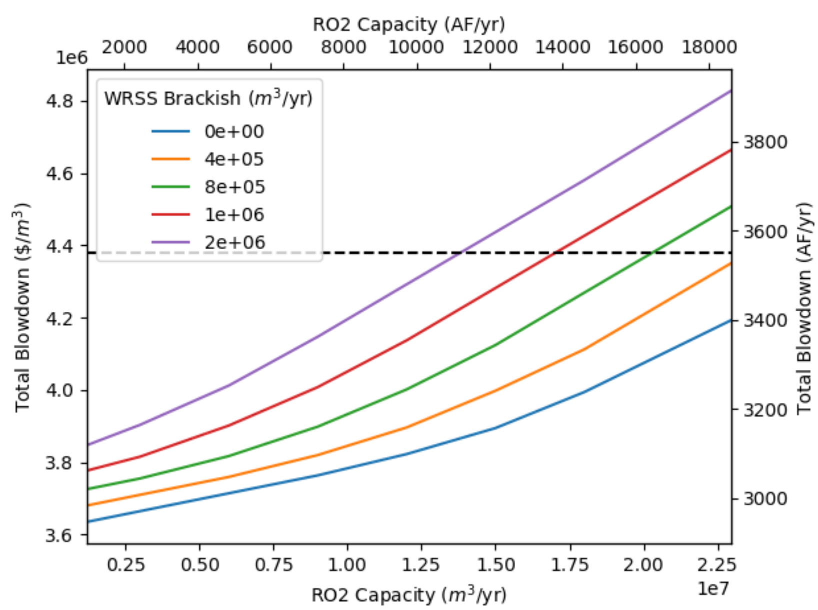


Figure 18. Total blowdown vs regional RO size as a function the pumped brackish water volume (different color lines). The RO1 size is fixed at 0.0% split stream, i.e. no RO1 is built. The black line indicates the maximum flow rate that the current evaporation ponds can handle.

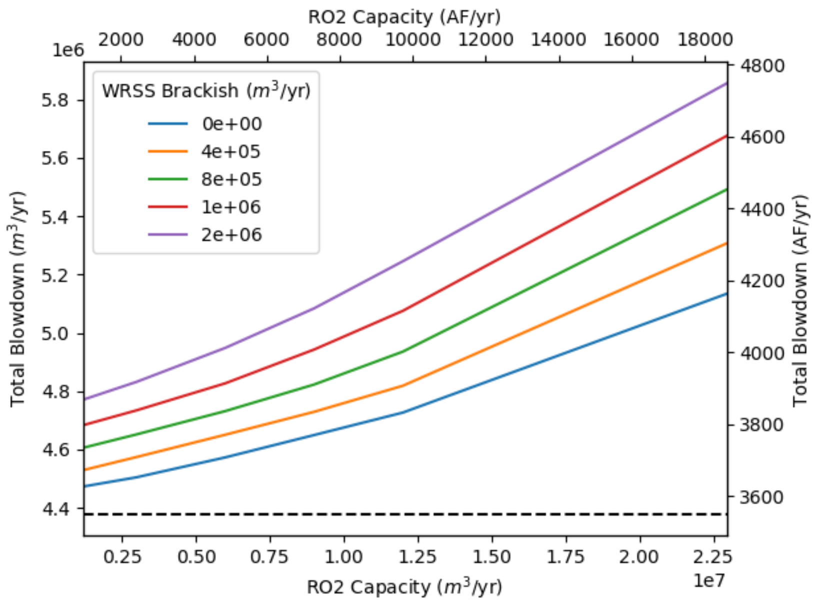


Figure 19. Total blowdown vs regional RO size as a function the brackish water directly into the WRSS (different color lines). The RO1 size is fixed at 5% split stream. The black line indicates the maximum flow rate that the current evaporation ponds can handle.

Water chemistry throughout the system (water salinity constraint)

The second constraint on the system is the time-averaged reservoir pond salinity (450 ppm of chlorides). This constraint is based on the administrative operational target for chloride concentration in the reservoir ponds. Considering this time-average constraint, the chloride concentration in the reservoirs is allowed to exceed the operational target salinity occasionally. However, the circulating water chemistry operational limit (12000 ppm chlorides) is respected at all times by adjusting the blowdown. Considering the time-average reservoir pond salinity as constraint, instead of directly the circulating water operational limit, assures that the cooling water quality at RPS is also within operational limits. To assess this constraint, let’s follow the water chemistry through the system. The brackish water flow rate directly into the WRSS, the regional RO wastewater concentrate, and effluent water are combined and sent to the WRF via the WRSS. The WRSS chloride concentrations are given for various regional RO concentrate flow rates (sizes) in Figure 20. For simplicity, only the case where the brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr) is shown. The reasoning for the salinity propagation through the system is the same for the case where no additional brackish water is injected into the WRSS. The chloride concentration scales approximately linear with regional RO concentrate flow rates, because the concentrate stream salinity is much higher than other streams. For reference, the chloride concentrations of the different streams are given in Table 13. Although the concentrate raises the salinity, it also offsets the use of effluent, creating a cost savings (see later when economics for this case are discussed). Additionally, the concentration in the WRSS is a function of RO1 size, because larger RO1s require more water (more RO1 concentrate is produced). Low salinity effluent water is bought to meet the excess, thus slightly diluting the WRSS.

Table 13: Water stream chloride concentrations.

Water stream	Chloride concentration [ppm]
RO concentrate	~1900
Brackish groundwater	~800
Municipal effluent year average year min/max	360 168/477

The WRF removes dissolved solids, as discussed in Section 3.3.3. Figure 21 and Figure 22, show the monthly concentrations of various constituents at the inlet and the outlet of the WRF, respectively. The shaded band of these plots represent the region (RO1 and RO2 sizes) in which the blowdown constraint is satisfied.

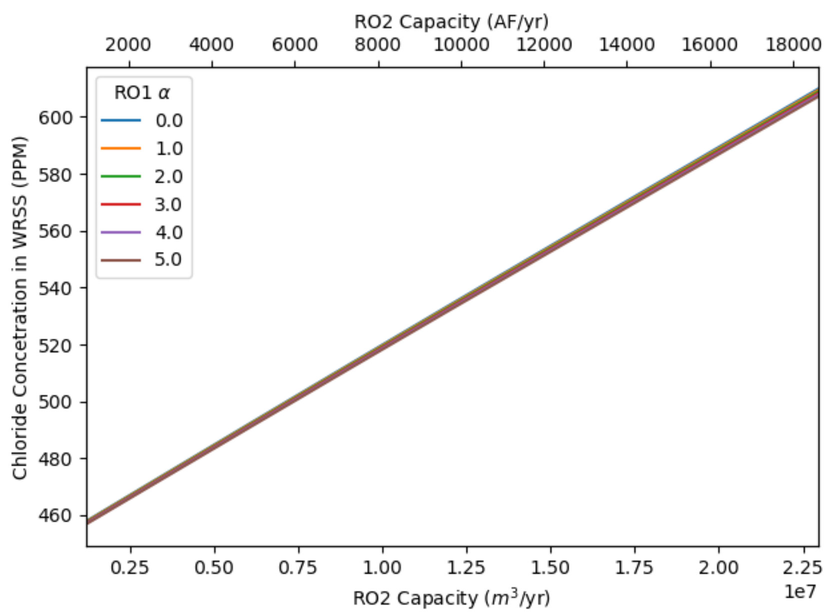


Figure 20. Chloride concentration in WRSS vs regional RO size as a function of RO1 alpha (different color lines). The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

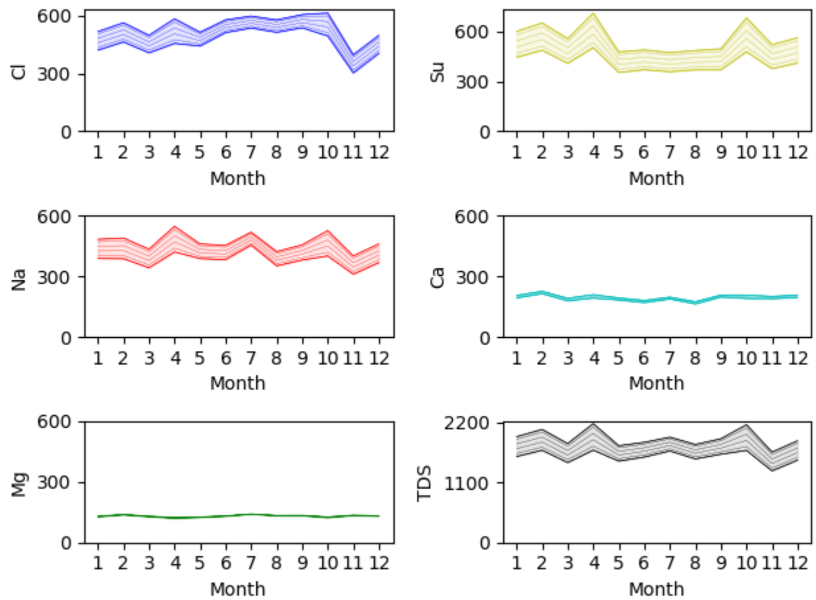


Figure 21. WRSS average monthly constituent concentrations. The shaded region is the band at which the physical blowdown constraint of the system is met (combinations of RO1 and RO2 sizes, brackish water directly into the WRSS fixed at 1.9e7 m^3/yr (15500 AF/yr)). The WRSS serves as the inlet to the WRF.

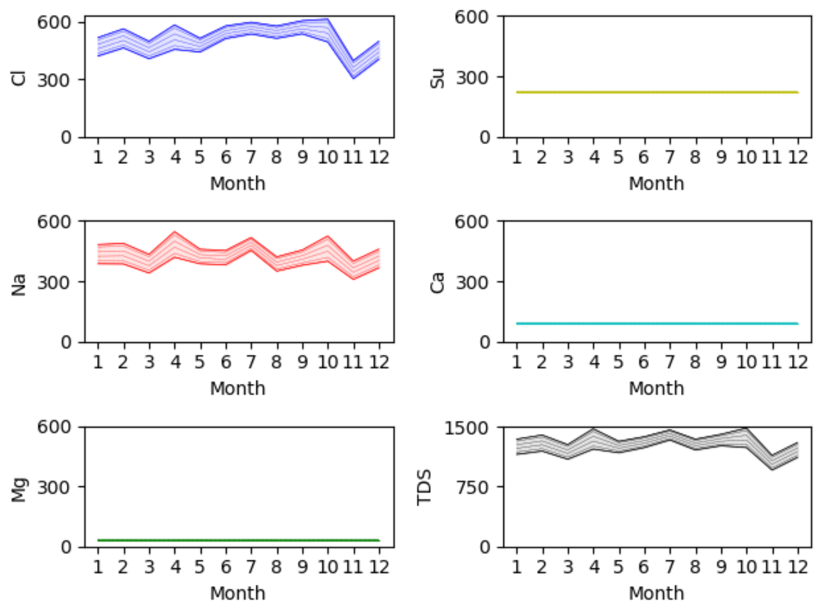


Figure 22. Average monthly constituent concentrations leaving the WRF. The shaded band represents feasible regions as in the inlet figure above.

After the water leaves the WRF, some portion of it is sent to the RO1 and the remaining water is sent directly to the reservoir. This RO1 split is varied and is the driver for the RO1 capacity. After the clean water leaves RO1 it is sent to the reservoir. RO1 operates at ~78% efficiency according to the RO model described in Section 3.3.2. The wastewater from RO1 is sent to the evaporation ponds. Figure 23 shows the average monthly chloride concentration of the reservoir for the systems within the physical blowdown constraint. Figure 24 shows the yearly average chloride concentration in the reservoir, plotted against the RO2 size and RO1 split sensitivities. One can see that, for the size of the regional RO that will hit the blowdown constraint, the chloride concentration in the reservoir will be over 450 ppm. For example, if no RO1 is built, the maximum regional RO size hitting the blowdown constraint is ~1.4e7 m^3/yr (10990 AF/yr), for which the chloride concentration in the reservoir is ~530 ppm. If one needs to stay below 450 ppm average chloride concentration in the reservoir, a RO1 of at least 3% slipstream is required (for 1.9e7 m^3/yr (15500 AF/yr) of brackish water directly into the WRSS), which produces more blowdown than the allowable limit, even if no regional RO is built. Considering this, to be able to build a reasonable size RO2 while still injecting brackish water into the WRSS (as seen in CASE 0, it is economically beneficial to inject as much brackish water into the WRSS as possible), one of the limits needs to be lifted; i.e., either additional evaporation ponds need to be built to allow for more blowdown, or the RPS plant needs to be adjusted to be able to accept saltier water for cooling. As already mentioned, assuming higher efficiencies for the RO plants will also likely change this picture.

Alternatively, the allowable RO2 size can also be increased by reducing the brackish water injected directly into the WRSS (this will likely lead to less favorable economics). Figure 25 shows the same as Figure 24; i.e., the yearly average chloride concentration in the reservoir plotted against the RO2 size and RO1 split sensitivities, but for no additional brackish water injected in the WRSS (compared to 1.9e7 m^3/yr (15500 AF/yr) in the reference case). The RO2 hitting the blowdown limit in this case is ~2.8e7 m^3/yr (23000 AF/yr) (see Figure 18 when no RO1 is built). The resulting chloride concentration is above 450 ppm. Keeping in mind that for the blowdown constraint only (see Figure 18 and Figure 19), the maximum RO2 size possible is decreasing with increasing RO1 size while for the salinity constraint (see Figure 25), the maximum RO2 size possible is increasing with increasing RO1 size, an optimum can be found. The optimum size of RO1 is ~ 2.3% slipstream, which leads to an maximum size RO2 of 1.5e7 m^3/yr (12500 AF/yr) not violating the reservoir pond chloride concentration of 450 ppm, in case no additional brackish water is injected in the WRSS. For reference, the size of RO2 not violating the reservoir pond chloride concentration of 450 ppm, in case no additional brackish water is injected in the WRSS and no RO1 is built is very close, i.e. ~1.4e7 m^3/yr (11000 AF/yr).

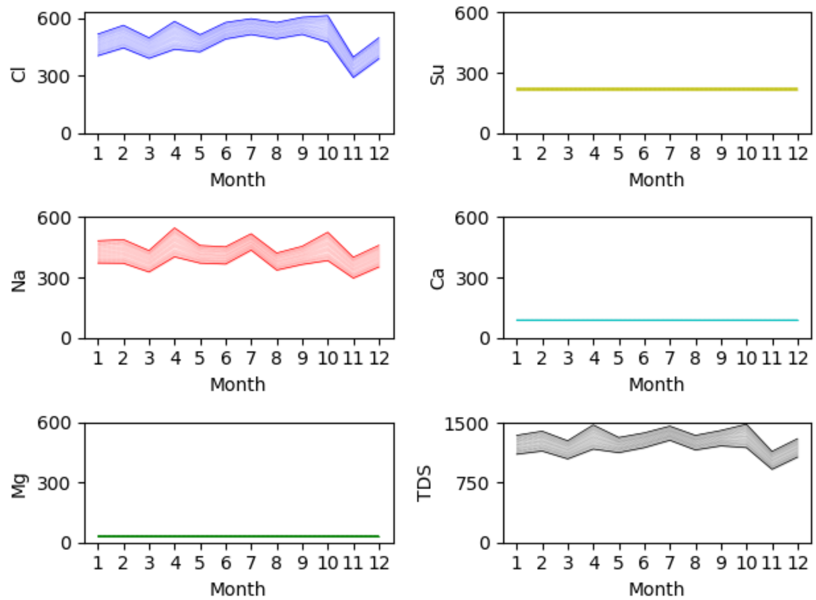


Figure 23. Reservoir average monthly concentrations for physically feasible combinations of RO1 and RO2 sizes (brackish water directly into the WRSS fixed at 1.9e7 m^3/yr (15500 AF/yr)).

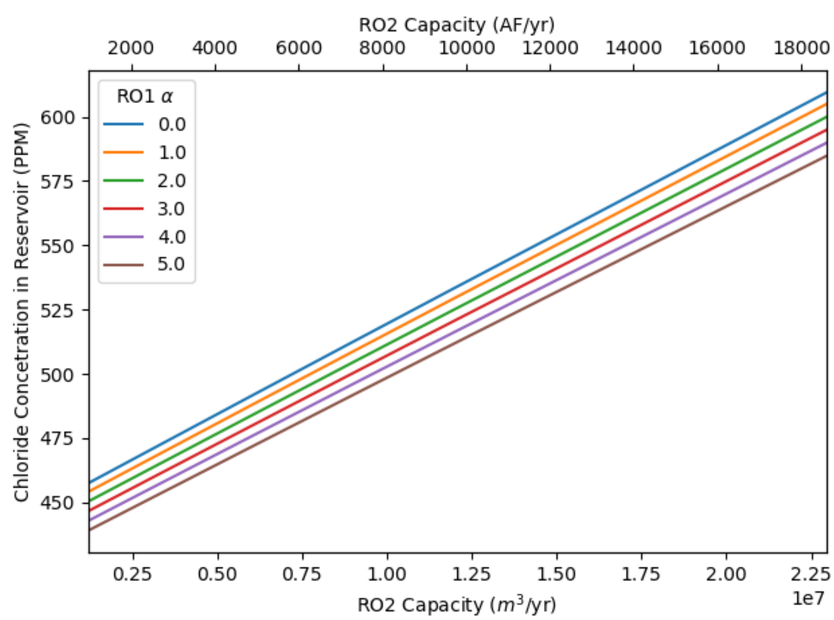


Figure 24. Average reservoir chloride concentration vs regional RO size as a function of RO1 alpha (different color lines). The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

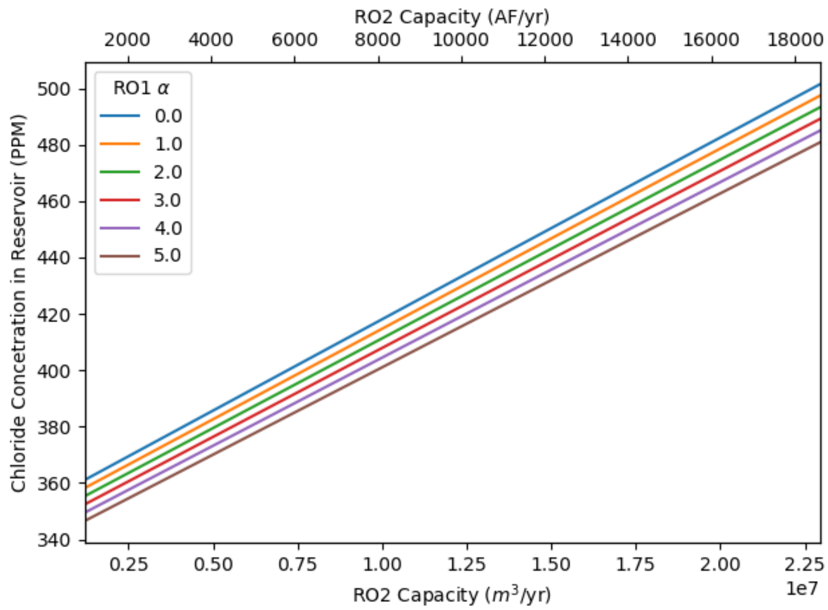


Figure 25. Average reservoir chloride concentration vs regional RO size as a function of α for RO1 (different color lines). The brackish water directly into the WRSS is set at 0 m^3/yr (0 AF/yr).

As the water leaves the reservoir, a portion is sent to the RPS plant and the rest is used to cool Palo Verde. The model includes Redhawk's cooling needs as a constraint, but focuses on the PVGS cooling requirements. The PV cooling requirement scales with increased salinity, shown in Figure 26. The maximum concentration versus the cooling blowdown is plotted. The blowdown scales linearly with the cooling tower inlet salinity for salinities over 450 ppm.

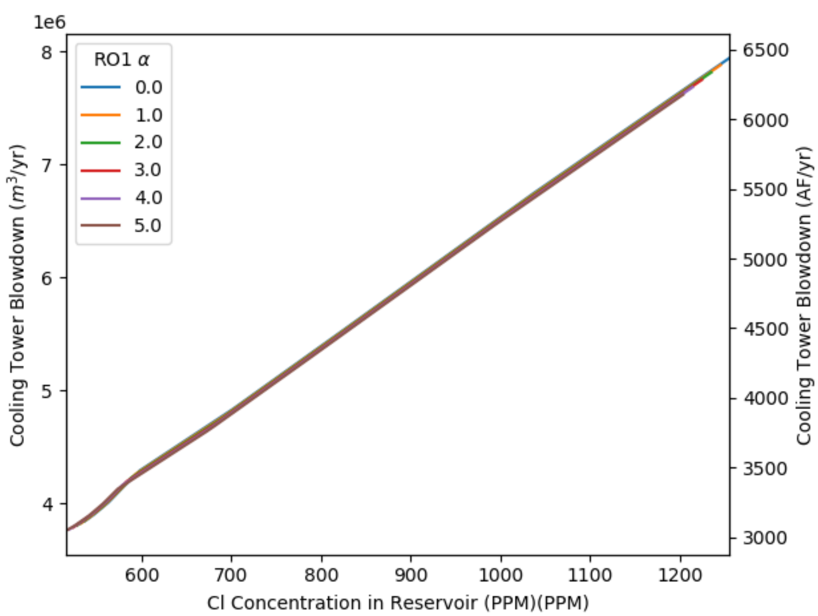


Figure 26. Cooling tower blowdown vs yearly average chloride concentration in the reservoir as a function of α for RO1 (different color lines).

Potable water generation and regional RO efficiency

Figure 27 shows potable water output of the regional RO2 as a function of its size. As discussed, for the case where the brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr), the maximum size of RO2 is 1.4e7 m^3/yr (10990 AF/yr); i.e., the maximum potable water produced while the blowdown constraint is satisfied is ~8.63e6 m^3/yr (7000 AF/yr). However, as discussed, the salinity constraint is not respected for that case. For the case where no additional brackish water is injected into the WRSS, the maximum size of RO2 (respecting salinity and blowdown constraints) is ~1.5e7 m^3/yr (12500 AF/yr) which leads to ~9.9e6 m^3/yr (8000 AF/yr) of potable water. The potable water exits the RO with dissolved chloride and sodium concentrations of ~18 ppm. Chemical concentrations of the waste stream from the regional RO2 are also given in Table 14.

Table 14: Concentrations of Regional RO waste stream.

Outlet stream	Waste (PPM)
Chlorides	1877.4
Sodium	1832.8
Calcium	423.0
Magnesium	188.0
Sulfur	2772.7
TDS	7093.9

The amount of potable water produced is highly dependent on the regional RO's efficiency. The brackish RO model used calculates the efficiency to be ~57%. This efficiency seems low for a brackish-water system, but the TDS of the brackish water is high, at 3263 ppm, when compared to a pre-treated stream that the RO model was originally designed for. A subsequent scenario, detailed in Section 4.2.3, adjusts RO efficiency as a sensitivity and discusses the implication of high-efficiency ROs on potable water production and waste water flow rates.

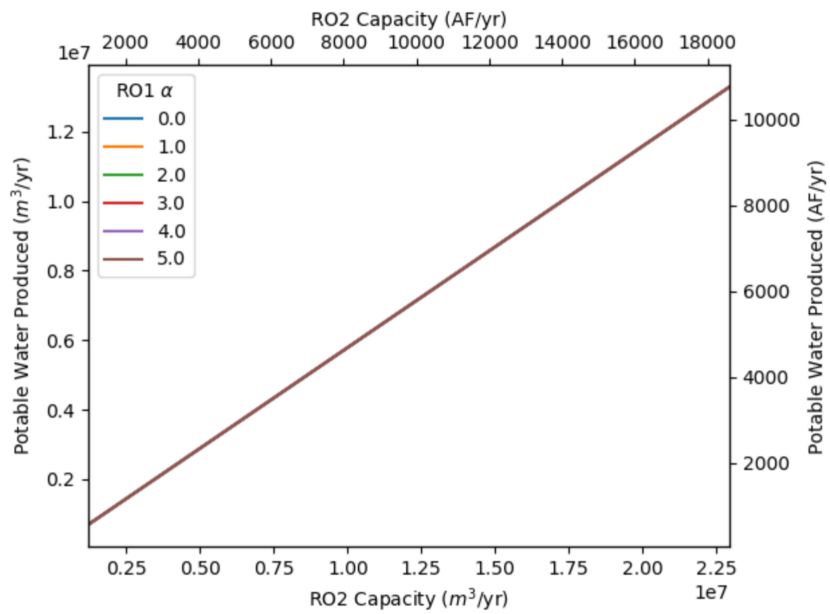


Figure 27. Potable water produced vs regional RO2 size as a function of α for RO1 (different color lines). Note that the potable water production is independent of RO1 size.

Economics

After discussing the physical boundary conditions, the economics of the system can be evaluated. As suggested in Section 3.4, the economics can be evaluated in two ways: (1) for APS and the regional RO as separate economic entities or (2) APS and the regional RO form one economic entity. The case of considering the whole system as one entity has more meaning if one can evaluate the NPV or IRR for the global system (instead of the LCOPW); i.e., for known potable water prices. The water market will be introduced in Section 4.2.4. For the base scenario in this section, the water market model is not used, and the LCOCT and LCOPW are evaluated; i.e., APS and the regional RO are considered separate entities.

First, the LCOCT is found for which CASE 1 $NPV^{CASE\ 1}$ matches $NPV^{CASE\ 0}$. The LCOCT is the cost that the regional RO pays APS to take and treat the concentrate, such that costs incurred by APS for extra treatment in the WRF or building an onsite RO are offset. Two cases are considered (see Section 3.4): (1) the LCOCT offsets the additional water treatment cost (RO1 CAPEX and O&M as well as any difference in WRF operating cost) as well as the savings in effluent water acquisition at APS; (2) the LCOCT offsets only the additional water treatment cost at APS.

LCOCT offsets the water treatment cost and effluent water cost savings

This first case is where the LCOCT offsets the water treatment cost and, in addition, also propagates the effluent water cost savings to the owner/operator of RO2; i.e., the economics (cooling water costs) for APS are unchanged compared to CASE 0 where no ROs are built. Before looking at the LCOCT and subsequent LCOPW for RO2, the details of how the cash flows behave are presented for a specific size of RO2 and brackish water into WRSS for illustration. First, Figure 28 presents the main cost drivers for CASE 0, while Figure 29 shows the main cost drivers for CASE 1. The cost is shown accumulated and discounted for the whole project life. Figure 30 shows the difference for each cash flow between the base CASE 0 and CASE 1 for a (small) fixed size of regional RO 1.2e6 m^3/yr (1000 AF/yr) and a fixed amount of brackish water intake into the WRSS 1.9e7 m^3/yr (15500 AF/yr). The plot shows the cost difference as a function of RO1 size (indicated as % slip stream), as in the two previous figures. One can see that:

- The RO1 capex grows linearly with RO1 size. Since there is no RO in CASE 0, this difference to CASE 1 is always positive.
- The cost of water treatment in the WRF increases slightly with RO1 size (bigger RO1 sizes lead to more water consumption). In the presented example case, this difference is always positive; i.e., the WRF water treatment costs more in CASE 1 compared to CASE 0 for all RO1 sizes.
- The effluent water cost has a cross point at ~3.5% RO1 slipstream size. For the example case considered, the amount of effluent water (the consequently the effluent water cost) is less in CASE 1 than CASE 0 for small sizes of RO1 and becomes more for bigger RO1 sizes.
- Considering the total water acquisition and treatment cost (shown in Figure 31),; i.e., the sum of the presented cash flows, one can see that for the presented case, the total water cost are less for CASE 1 compared to CASE 0 for small sizes of RO1 (up to ~0.3% of slip stream).

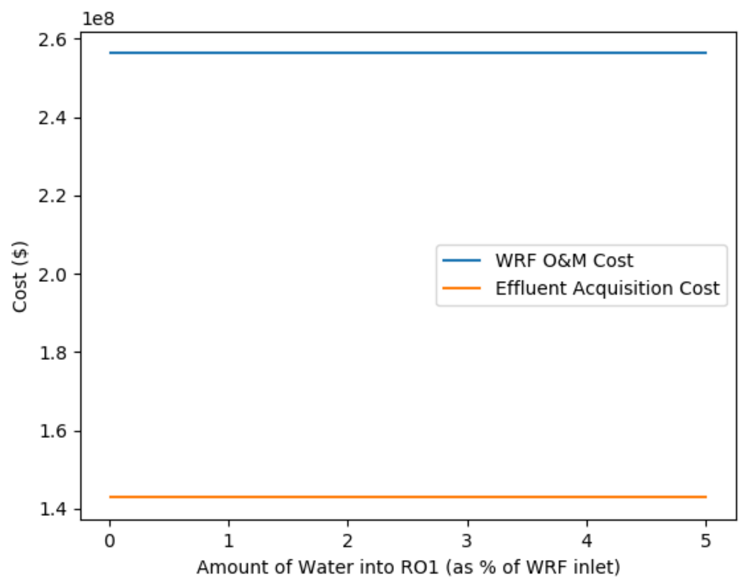


Figure 28. Driving costs for CASE 0. Brackish water pumping costs are not shown, because they are consistent across CASE 0 and CASE 1 for the selected example. Brackish water intake into the WRSS is 1.9e7 m^3/yr (15500 AF/yr) and regional RO size is 1.2e6 m^3/yr (1000AF/yr).

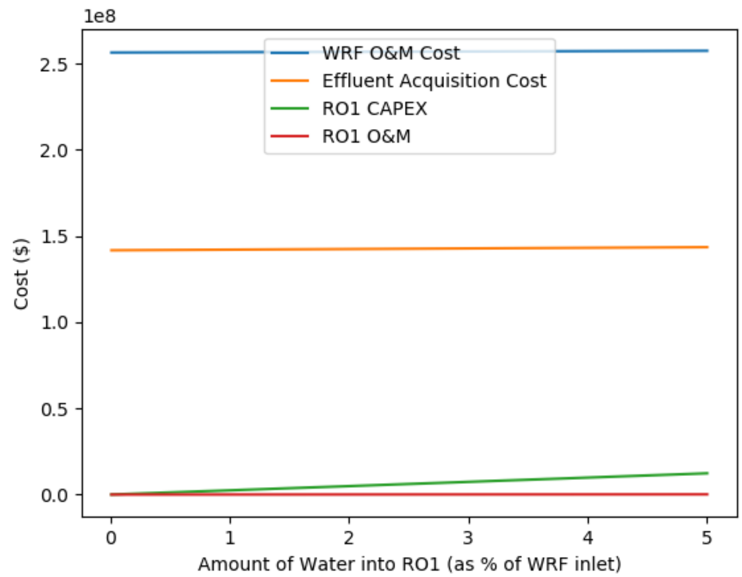


Figure 29. Driving costs for CASE 1. Brackish water pumping costs are not shown, because they are consistent across CASE 0 and CASE 1 for the selected example. Brackish water intake into the WRSS is 1.9e7 m^3/yr (15500 AF/yr) and regional RO size is 1.2e6 m^3/yr (1000AF/yr).

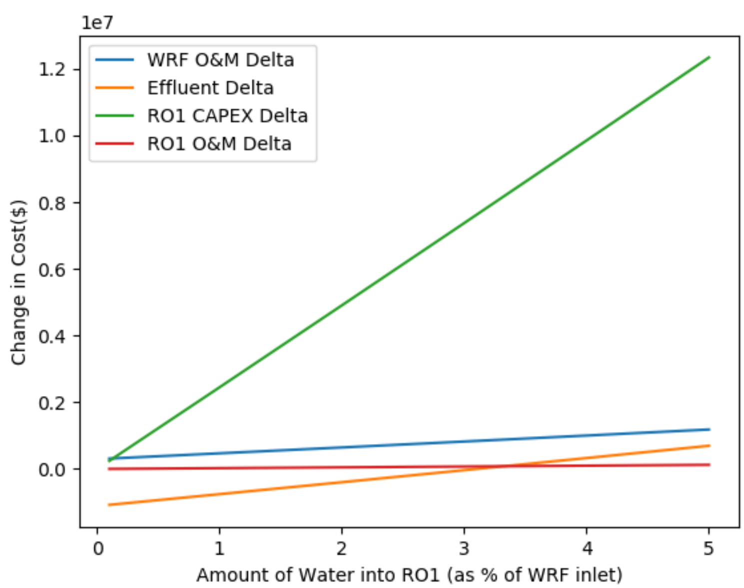


Figure 30. Change in cost parameters between CASE 0 and CASE 1. A negative number represents a greater cost in CASE 0 vs CASE 1; i.e., a cost saving in CASE 1 compared to CASE 0. Brackish water pumping costs are not shown, because they are consistent across CASE 0 and CASE 1 for the selected example. Brackish water intake into the WRSS is 1.9e7 m^3/yr (15500 AF/yr) and regional RO size is 1.2e6 m^3/yr (1000AF/yr).

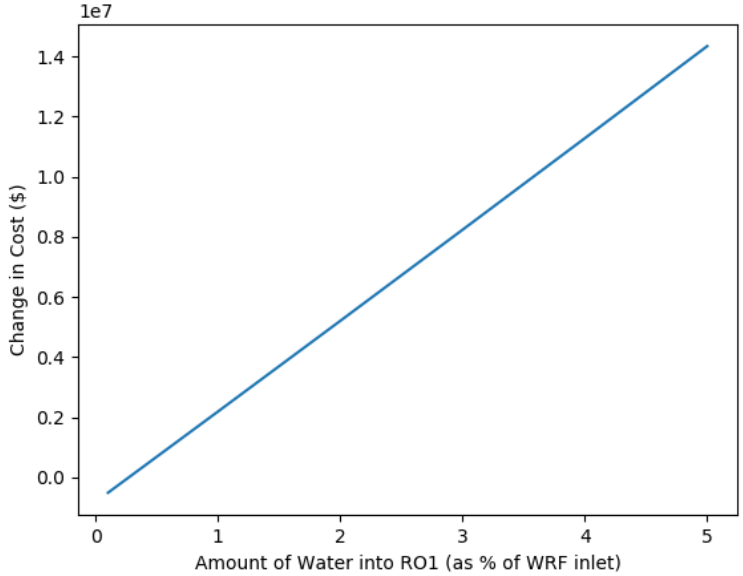


Figure 31. Change in total cost from CASE 0 to CASE 1. A negative number represents higher costs in CASE 0; i.e., a cost saving in CASE 1 compared to CASE 0. Brackish water intake into the WRSS is 1.9e7 m^3/yr (15500 AF/yr) and regional RO size is 1.2e6 m^3/yr (1000AF/yr).

For additional information, Figure 32 shows the equipment cost driver for the regional RO as a function of its size.

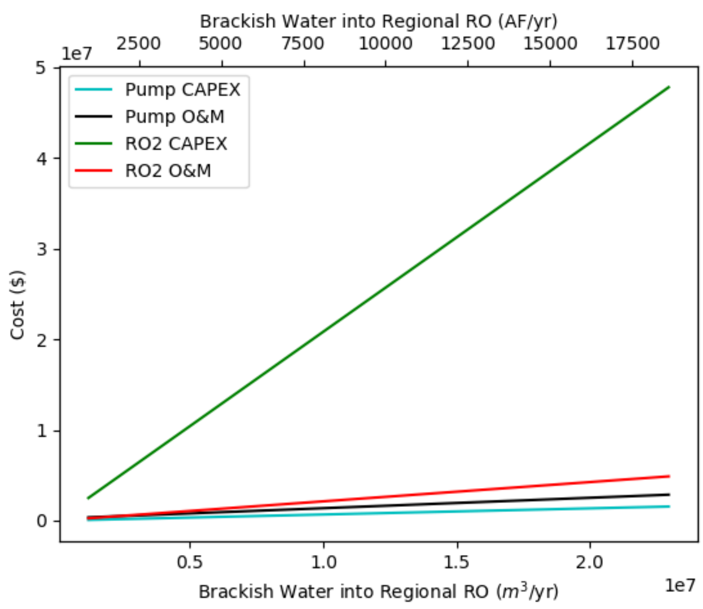


Figure 32. Equipment cost drivers for the regional RO system. O&M costs include electricity consumption.

After illustrating the behavior of the different cash flows for one selected case, Figure 33 and Figure 34 show the LCOCT and LCOPW as a function of regional RO size for different RO1 sizes. As mentioned, first, the LCOCT that offsets the water treatment cost and also propagates the effluent water cost savings to the owner/operator of RO2 is found. After finding the LCOCT, NPV_{RO2} is set to zero (assuming fair economical profit for RO2) and the LCOPW is computed. This cost represents the threshold cost at which potable water must be sold to achieve a zero (or positive) NPV for RO2. The plots assume a fixed amount of brackish water injected directly into the WRSS (1.9e7 m^3/yr (15500 AF/yr)). To estimate the sensitivity of the brackish water injected directly into the WRSS, Figure 35 to Figure 38 show the LCOCT and LCOPW vs regional RO size, as a function of brackish water injected directly into the WRSS for two selected sizes of RO1. It is worth noting that:

- As the size of the regional RO increases, the LCOCT decreases. This is because the concentrate offsets the need for effluent water, reducing the overall water acquisition cost at APS.
- The LCOCT is also a function of RO1 size. Since a bigger RO1 will lead to more water consumption (more concentrate from RO1), the water cost will rise and so will the LCOCT.
- As shown for the detailed cash flows above, the water acquisition and treatment cost may be bigger in CASE 0 compared to CASE 1 for some cases with a small RO1 or a big RO2; i.e., the savings in effluent water acquisition (considered over the project lifetime) outweighs the cost of building the onsite RO1 at PVGS. In that case the LCOCT is negative. The analysis does not consider APS paying for RO2 concentrate, but rather sets the LCOCT to zero for these cases.
- LCOCT is between 0 and ~3.5 $/m^3. However, LCOCT is lower than 0.5 $/m^3 for reasonable RO1 and RO2 sizes.
- LCOPW shows the same behavior as LCOCT.
- LCOPW flattens out at about 0.55 $/m^3 in the regions where the LCOCT becomes 0. The maximum LCOPW is about ~3 $/m^3 with LCOPW lower than 1.0 $/m^3 for reasonable RO1 and RO2 sizes.
- LCOCT and, consequently, LCOPW decreases with amount of brackish water directly injected into the WRSS since more brackish water means less more-expensive effluent water has to be purchased.

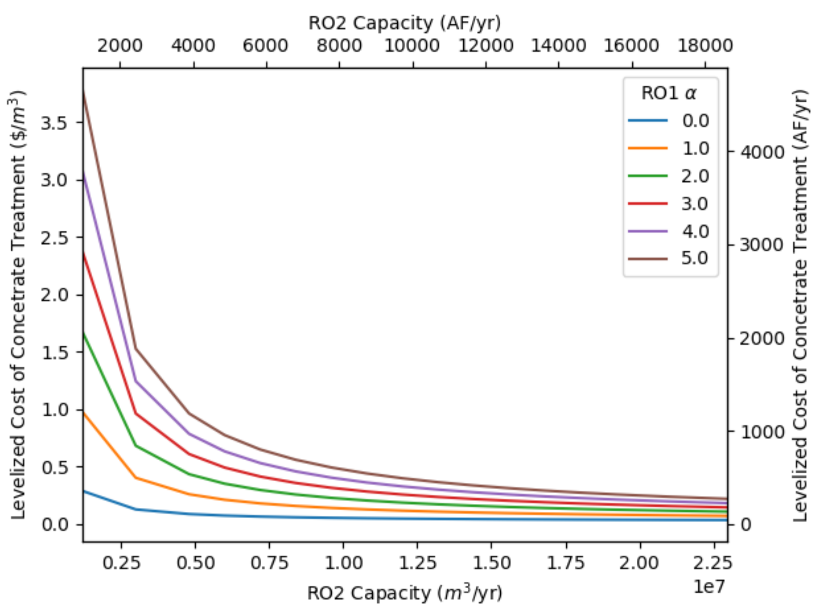


Figure 33. Levelized cost of concentrate treatment (LCOCT) vs RO2 size for selected RO1 sizes (alpha) (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

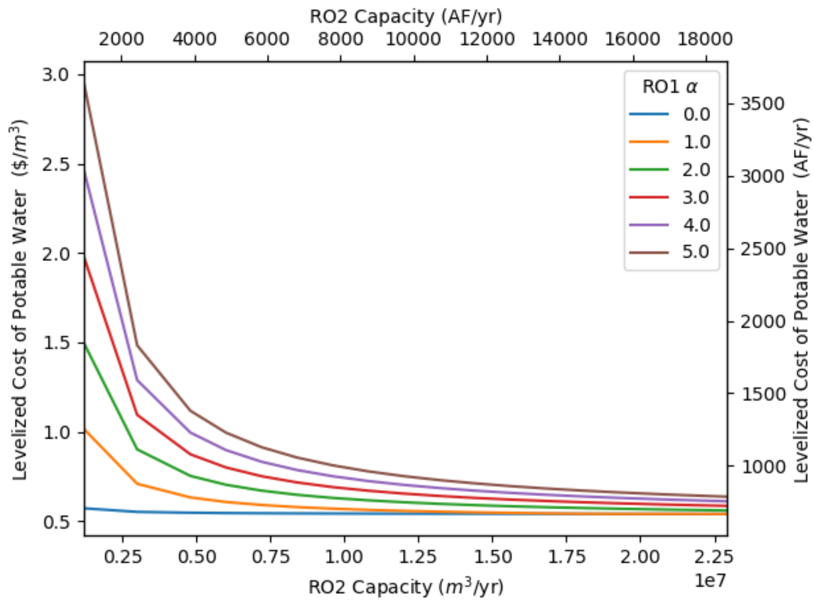


Figure 34. Levelized cost of potable water (LCOPW) vs RO2 size as a function of RO1 alpha (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

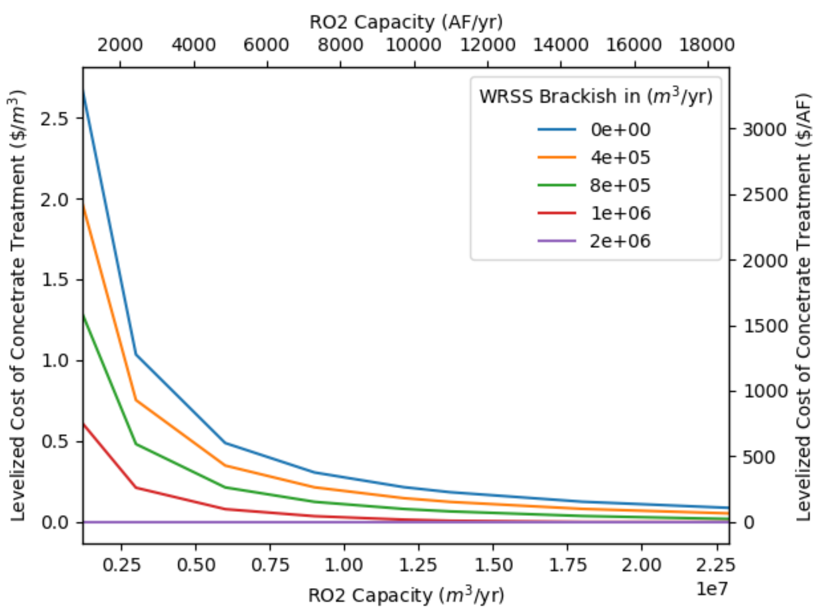


Figure 35. Levelized cost of concentrate treatment (LCOCT) vs RO2 size as a function of the pumped brackish water (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The RO1 size is fixed at 0.0% split stream; i.e., no RO1 is built.

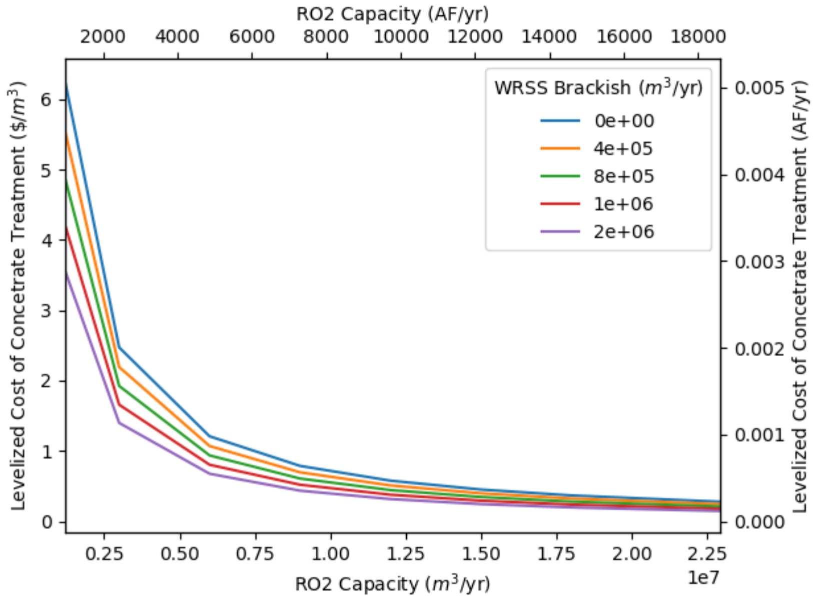


Figure 36. Levelized cost of concentrate treatment (LCOCT) vs RO2 size as a function of the pumped brackish water (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The RO1 size is fixed at 5% split stream.

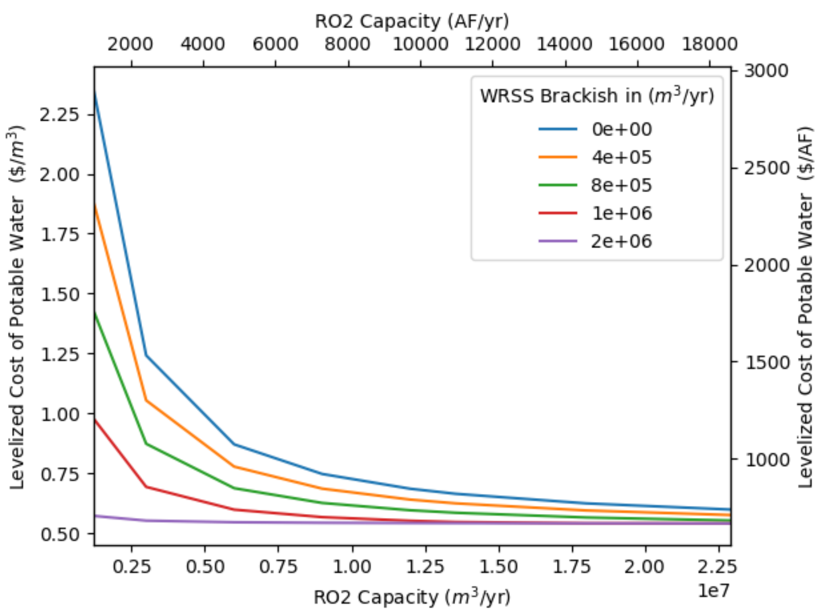


Figure 37. Levelized cost of potable water (LCOPW) vs RO2 size as a function of the pumper brackish water (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The RO1 size is fixed at 0.0% split stream; i.e., no RO1 is built.

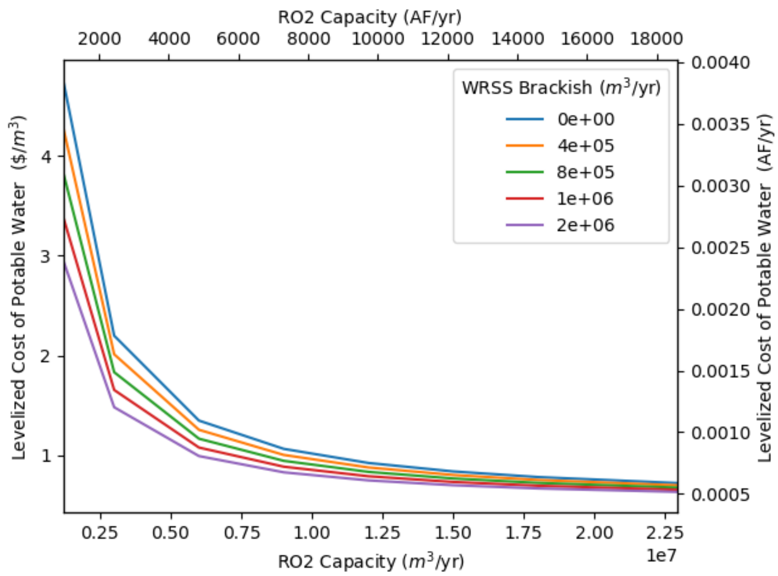


Figure 38. Levelized cost of potable water (LCOPW) vs RO2 size as a function of the pumper brackish water (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The RO1 size is fixed at 5% split stream.

Other selected costs for the reference case are included in Table 15, where the brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The table includes only the limits of the RO1 alpha and brackish input sensitivities.

LCOCT offsets only the water treatment cost

The second case is where the LCOCT offsets only the water treatment cost, while the effluent water cost savings are kept to APS. Figure 39 through Figure 42 show the LCOCT and LCOPW as a function of regional RO size for different RO1 sizes and different amounts of brackish water injected directly into the WRSS. First the LCOCT that offsets only the water treatment cost is found. After finding the LCOCT, NPV_{RO2} is set to zero and the LCOPW is computed. This cost represents the threshold cost that potable water must be sold at to achieve a zero (or positive) NPV for RO2. Comparing this to the earlier case where the LCOCT offsets everything, one can see that:

For the case where 1.9e7 m^3/yr (15500 AF/yr) of brackish water are injected into the WRSS:

- The LCOCT is somewhat higher ranging from 0.25 to 3.8 $/$m^3$ for small RO2s compared to 0 to 3.5 $/$m^3$ in the previous case where the LCOCT also offsets the water acquisition savings.
- The tangential cost of LCOCT for bigger RO2s is ~0.2 $/$m^3$ compared to negative (zero) values in the previous case where the LCOCT also offsets the water acquisition savings.
- The LCOPW ranges from 0.75 to 3.0 $/$m^3$ for small RO2s. Which is also somewhat higher compared to the previous case where the LCOCT also offsets the water acquisition savings. This corresponds to the increase in LCOCT between the cases.
- For large RO2s, LCOPW is ~0.7 $/$m^3$ compared to 0.6 $/$m^3$ in the previous case where the LCOCT also offsets the water acquisition savings. This indicates that the water treatment cost is about ~0.1 $/$m^3$ higher compared to the case where LCOCT offsets the water treatment cost and effluent water savings. To get an order of magnitude, the effluent water savings at APS, i.e. the difference on water cost between the two cases where LCOCT offsets all or only the water treatment cost would be (for a RO2 size of 1.4e7 m^3/yr (11000 AF/yr)) ~ 500000 $/yr.

Table 15: Economic Drivers for Physically Feasible Boundary Runs, Model Year 1 (million$/yr).

Parameter	0% RO1 split small RO2	0% RO1 Split big RO2	2% RO1 Split small RO2
Effluent Water Cost	8.81	8.25	8.84
Brackish Water Cost	0.39	0.39	0.39
Regional RO CAPEX	2.5e6	47.8e6	2.5e6
Regional RO Electricity Cost	0.02	0.30	0.02
Regional RO Brackish Water	0.39	0.27	0.39
WRF Variable O&M	25.91	26.25	25.94
WRF Electricity	1.89	1.88	1.87
PV RO CAPEX	0.0	0.0	4.9e6
PV RO Electricity Cost	0.0	0.0	0.04

For the case where no additional brackish water are injected into the WRSS:

- The difference in LCOCT and LOCPW between the case where the LCOCT offsets only the water treatment costs and the case where the LCOCT also offsets the water acquisition savings vanish. This indicates that the small savings in effluent water made in case brackish water is injected directly into the WRSS are reduced when no brackish water is injected. Remember that CASE 0 always includes 1.9e7 m^3/yr (15500 AF/yr) of brackish water injected into the WRSS. If for CASE 1, this direct injection is replaced by effluent water, the savings in its acquisition vanishes.

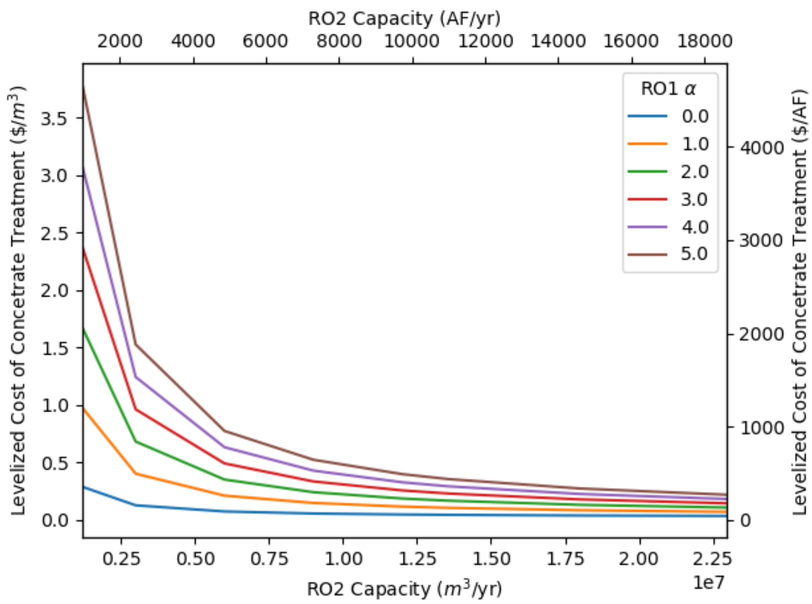


Figure 39. Levelized cost of concentrate treatment (LCOCT) vs RO2 size for selected RO1 sizes (alpha) (different color lines). LCOCT offsets only the water treatment cost. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

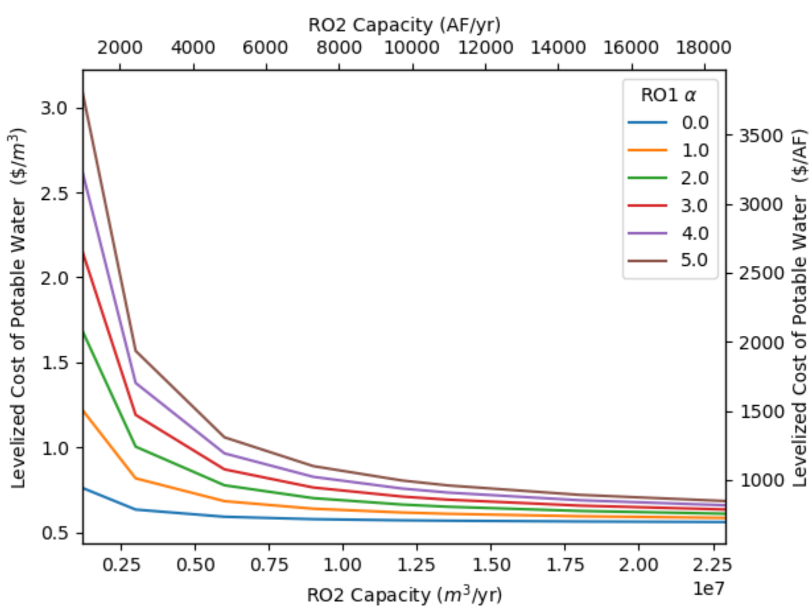


Figure 40. Levelized cost of potable water (LCOPW) vs RO2 size as a function of RO1 alpha (different color lines). LCOCT offsets only water treatment cost. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

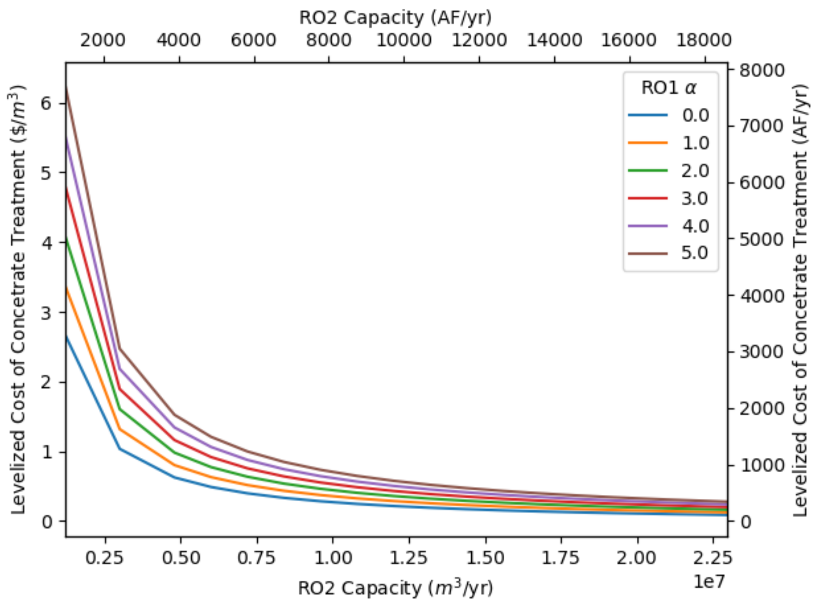


Figure 41. Levelized cost of concentrate treatment (LCOCT) vs RO2 size for selected RO1 sizes (alpha) (different color lines). LCOCT offsets only water treatment cost. The brackish water directly into the WRSS is set to 0 m^3/yr (0 AF/yr).

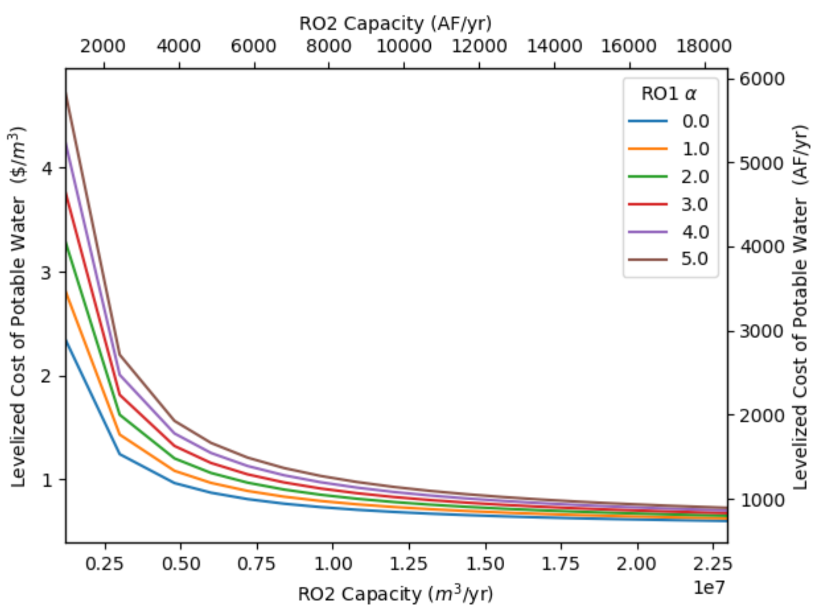


Figure 42. Levelized cost of potable water (LCOPW) vs RO2 size as a function of RO1 alpha (different color lines). LCOCT offsets only water treatment cost. The brackish water pumped directly into the WRSS is set to 0 m^3/yr (0 AF/yr.).

4.2.2 Scenario 2: Economic Sensitivities: Discount Rate and Year of Retirement

The second scenario investigates economic sensitivities and their effects on the system. Section 4.1 itemized the initial values and economic sensitivities for this case. The discount rate at APS as well as at the regional RO is varied between 5% and 15%. The number of years (project lifetime) is adjusted from 27 to 47, simulating PVGS receiving a subsequent license extension rather than retiring. The electricity wholesale price is also manipulated to investigate the impacts of price fluctuations on LCOPW and LCOCT. Each sensitivity is run on a selected case from scenario 1. As each sensitivity is run, all others are fixed at original values; i.e., when the discount rate is manipulated the reactor lifetime is fixed at 27 years.

As the discount rate increases, LCOCT and LCOPW increase. The LCOCT and LCOPW are given in Figure 43 and Figure 44, respectively (RO2 size of 3.6e7 m3/yr (29186 AF/yr), RO1 alpha is 5.0% and 1.9e7 m^3/yr (15500 AF/yr) brackish water into WRSS).

Operating the plant for 47 years instead of 27 led to a slight decrease in LCOCT and LCOPW. The results are given in Table 16 (RO2 size of 1.2e6 m3/yr (972 AF/yr), RO1 alpha is 5.0% and 1.9e7 m^3/yr (15500 AF/yr) brackish water into WRSS). Retiring the plant later would spread the capital costs over a greater time period.

Table 16: PV Operating Life Effect on Costs.

Economic Parameters	PVGS Life 27 Years	PVGS Life 47 Years
LCOCT ($/$m^3$)	3.56	3.33
LCOPW ($/$m^3$)	2.95	2.76

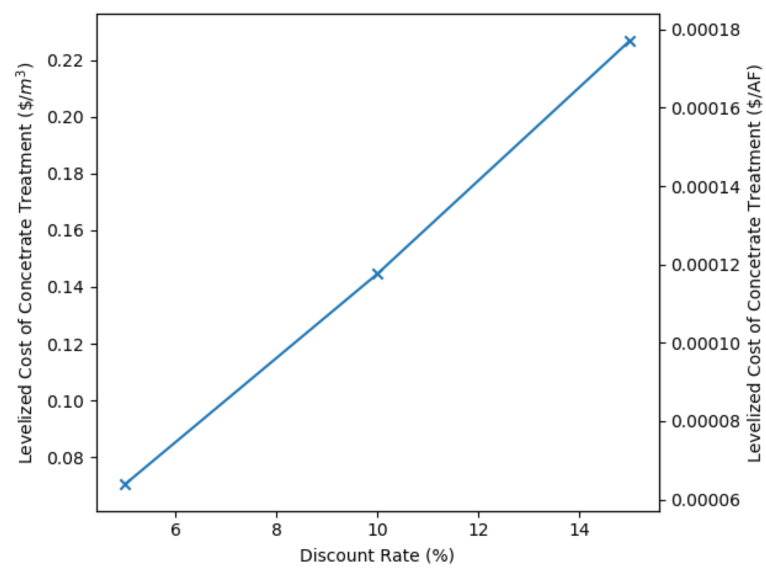


Figure 43. Levelized cost of concentrate treatment (LCOCT) vs discount rates (same discount rate is assumed for APS and RO2). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). RO2 size is 3.6e7 m^3/yr (29186 AF/yr) and no RO1 alpha is 5.0%.

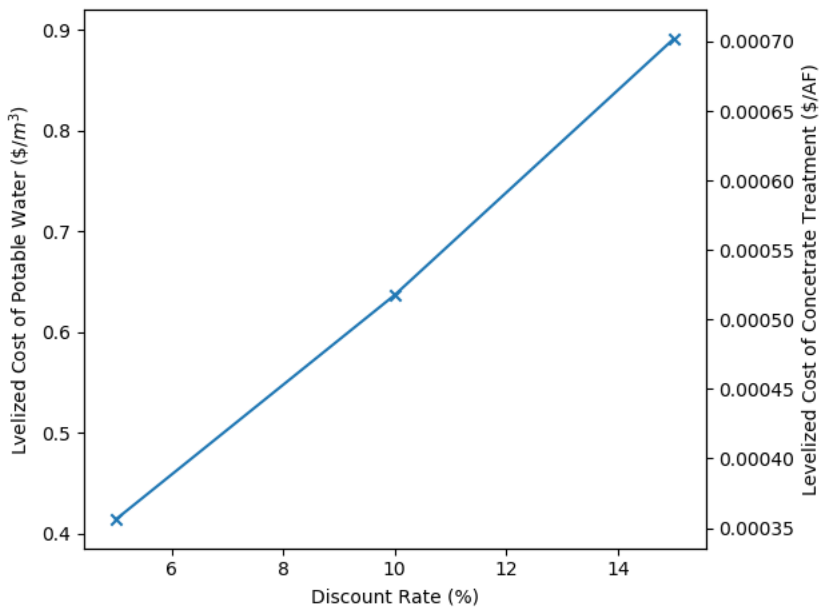


Figure 44. Levelized cost of potable water (LCOPW) vs discount rates (same discount rate is assumed for APS and RO2). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). RO2 size is 3.6e7 m^3/yr (29186 AF/yr) and no RO1 alpha is 5.0%.

4.2.3 Scenario 3: RO Efficiency Sensitivity Study

Each of the previous scenarios represents nominal cases in RO efficiency as predicted by the RO model described in Section 3.3.2. Because RO technology could generally reach upwards of 90% efficiency (depending on the type of membrane used and RO operating conditions), the 57% for the regional RO from this RO model might be overly conservative. While the assumed costs in the model represent an industry average, the efficiency may be lower compared to different commercial options. This scenario varies the regional RO efficiency between 60% and 90% efficiency. The effect on potable water production is plotted in Figure 45. The 90%-efficient RO can produce 20.6e6 m^3/yr (16700 AF/yr) potable, while still satisfying the blowdown boundary conditions.

As the regional RO efficiency increases, there is a tradeoff between amount of concentrate water that PVGS is paid to take and how much water can be sold. Lower efficiencies mean that PVGS needs to acquire less effluent water because the concentrate flow rate is higher. Two illustrative examples are shown. The first example shown considers the case where no RO1 is built and 1.9e7 m^3/yr (15500 AF/yr) of brackish water are injected into the WRSS. The LCOCT that offsets all, the water treatment cost and water acquisition savings for this case is below zero for all RO2 efficiencies between 60 and 90%. Figure 46 shows the corresponding LCOPW. For the second example, Figure 47 and Figure 48 show the LCOCT and LCOPW, respectively, as a function of RO2 efficiency for the case where no RO1 is built and the LCOCT offsets the water treatment cost and water acquisition savings, like in the first example. However, the amount of brackish water are injected into the WRSS is 0 m^3/yr (0 AF/yr).

The higher efficiency systems have a higher cost of concentrate treatment because the concentrate stream sent to PVGS is much more concentrated, i.e. less water. Thus, first, less effluent water cost is offset and second, the offset RO1 capex cost (which is independent of the amount of concentrate volume, but only depends on the total amount of salt coming from RO2) per volume concentrate becomes higher. The LCOPW decreases with RO efficiency because the higher efficiency ROs produce more potable water.

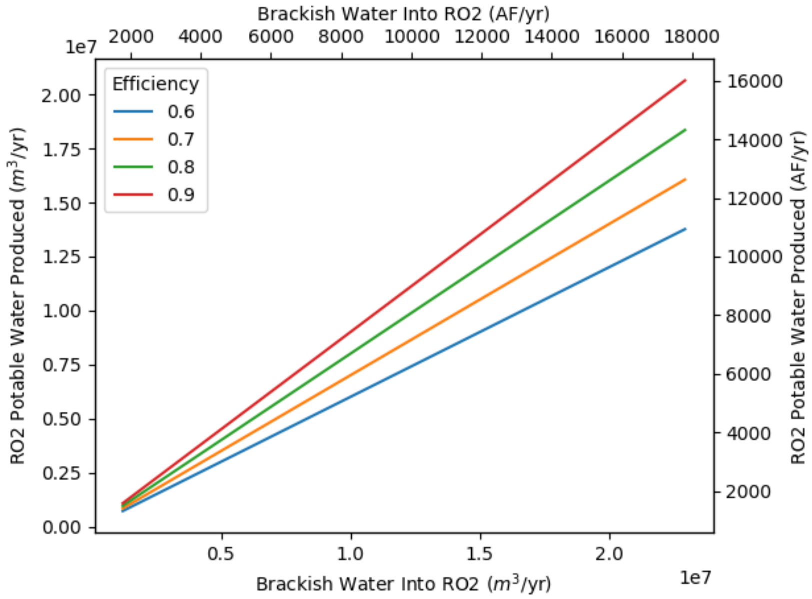


Figure 45. Regional RO efficiency effect on potable water production.

This preliminary scenario study assumes that the capex of the RO is independent of efficiency. In reality, increasing RO2 efficiency would likely increase its capex and O&M costs. Potential future work could include to quantify and compare this capital cost increase against the costs of building more evaporation ponds to increase blowdown limits and using cheaper lower efficiency RO technology.

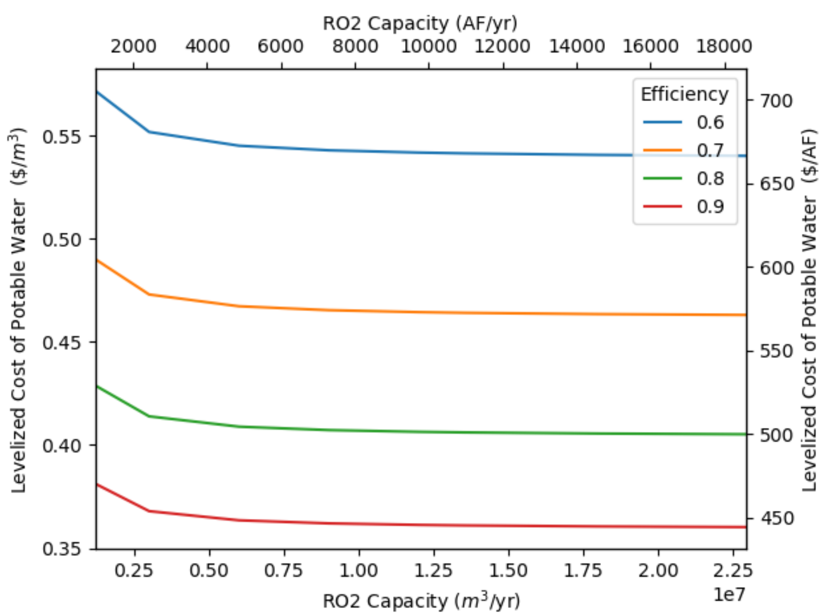


Figure 46. Levelized cost of potable water (LCOPW) vs RO2 size as a function of RO2 efficiency (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The RO1 size is fixed at 0.0% split stream; i.e., no RO1 is built.

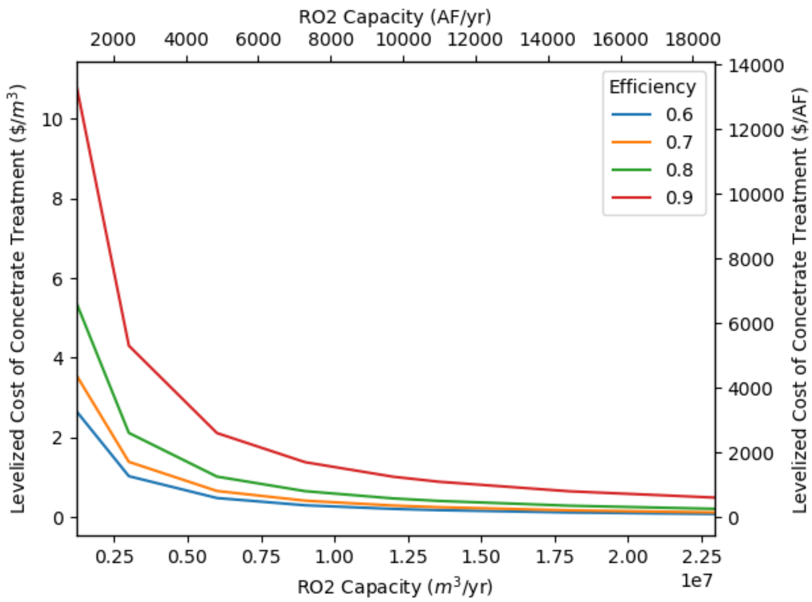


Figure 47. Levelized cost of concentrate treatment (LCOCT) vs RO2 size as a function of RO2 efficiency (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set to 0 m^3/yr (0 AF/yr). The RO1 size is fixed at 0.0% split stream; i.e., no RO1 is built.

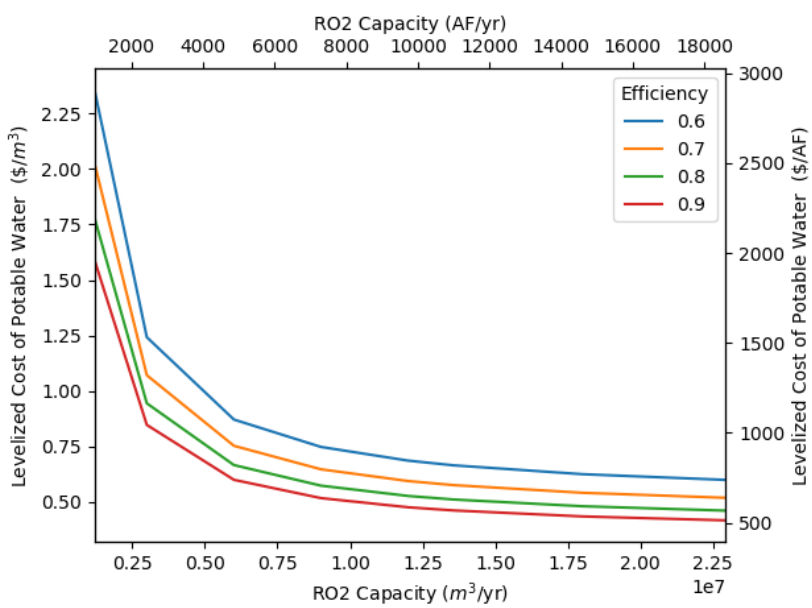


Figure 48. Levelized cost of potable water (LCOPW) vs RO2 size as a function of RO2 efficiency (different color lines). LCOCT offsets water treatment cost and water acquisition savings. The brackish water pumped directly into the WRSS is set to 0 m^3/yr (0 AF/yr). The RO1 size is fixed at 0.0% split stream; i.e., no RO1 is built.

4.2.4 Scenario 4: Water Market

The next scenario incorporates the municipal growth and water price models set forth in Section 3.5. It is assumed that the water produced from the regional RO is sold to four municipalities including Buckeye, Goodyear, Tolleson and Avondale.

To evaluate the economics of APS and the regional RO, two scenarios have been considered: First, the case where all four municipalities start buying water from the regional RO immediately after the regional RO is built; and second, the case where the municipalities start participating at a 5-year interval.

4.2.4.1 All considered municipalities purchase water from the regional RO as soon as it is available

The projected yearly demand for each municipality is plotted in Figure 49 and initial population and assumed population growth rate are given in Table 17.

If potable water produced in the regional RO is less than the projected monthly demand for each municipality, meaning that the regional RO produces less than the municipalities' consumption, the water is sold to all municipalities proportional to their respective population. The water price for each municipality is at the equilibrium as calculated in Eq. 58. This assumes that there are other water sources to meet municipalities' demand; i.e., water price will not spike as it would if the regional RO is considered the only water supplier. An example of this case is illustrated in Figure 50 and Figure 51, which show the projected water demand and the RO water provided for the four municipalities (for a small 1.2e6 m^3/yr (1000AF/yr) regional RO), as well as the projected water prices for that scenario. Note that even if insufficient water is produced to satisfy the demand, the water price does not increase. This is a result of the assumption that other water sources exist and water is sold at the equilibrium price. The equilibrium price is evaluated for each municipality separately for their respective demand.

Table 17: Initial 2018 Municipality Parameters.

Municipality	Population	Population Growth Rate
Buckeye	76815	4.75%
Goodyear	84035	2.96%
Tolleson	7319	1.36%
Avondale	86265	1.48%

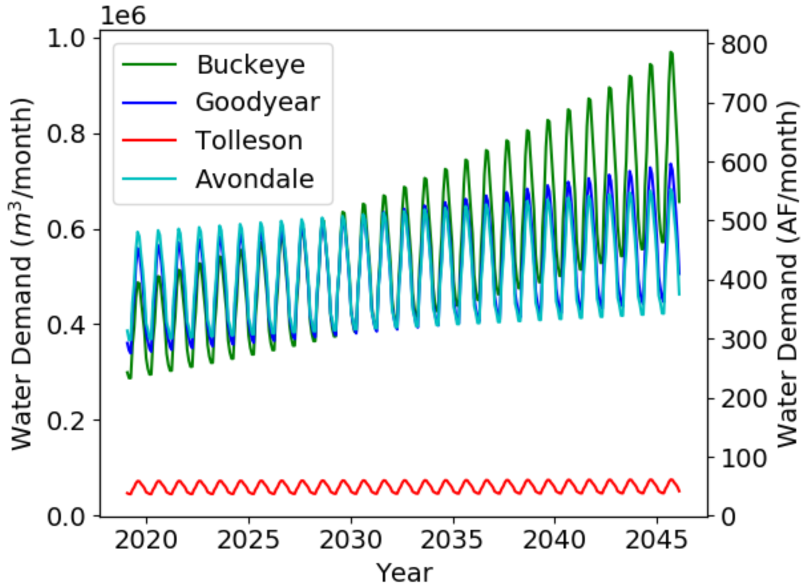


Figure 49. Municipality water demand growth projection.

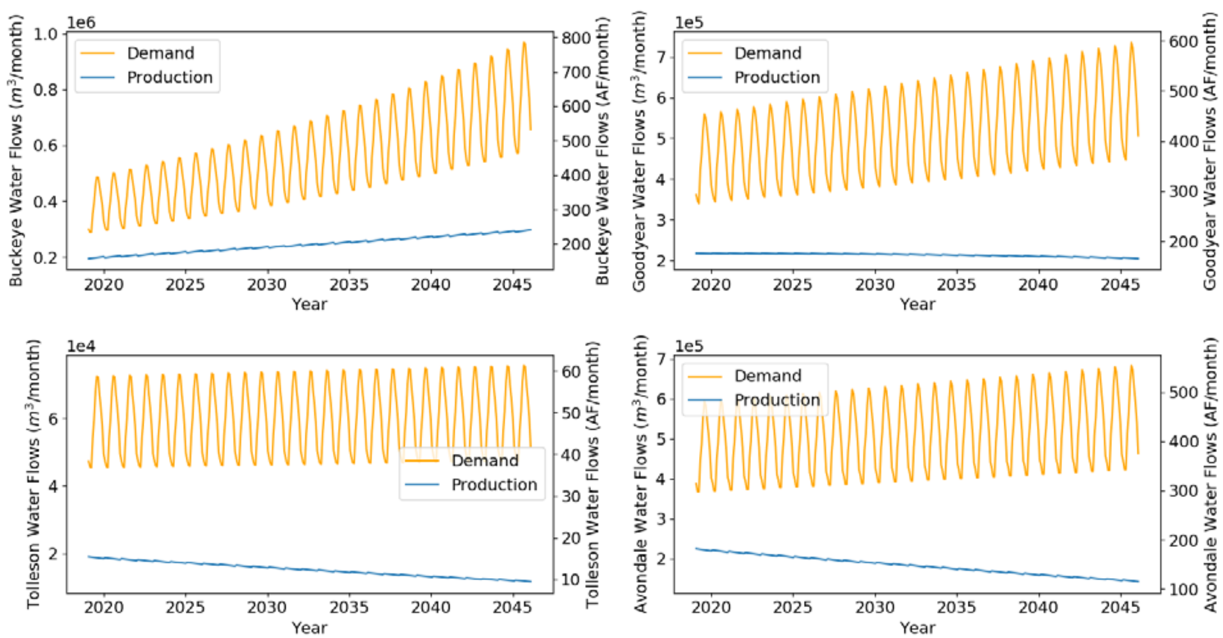


Figure 50. Projected water demand and regional RO production by municipality. Analysis is for an RO2 with a size of 1.2e6 m^3/yr (1000AF/yr), the smallest regional RO in this analysis.

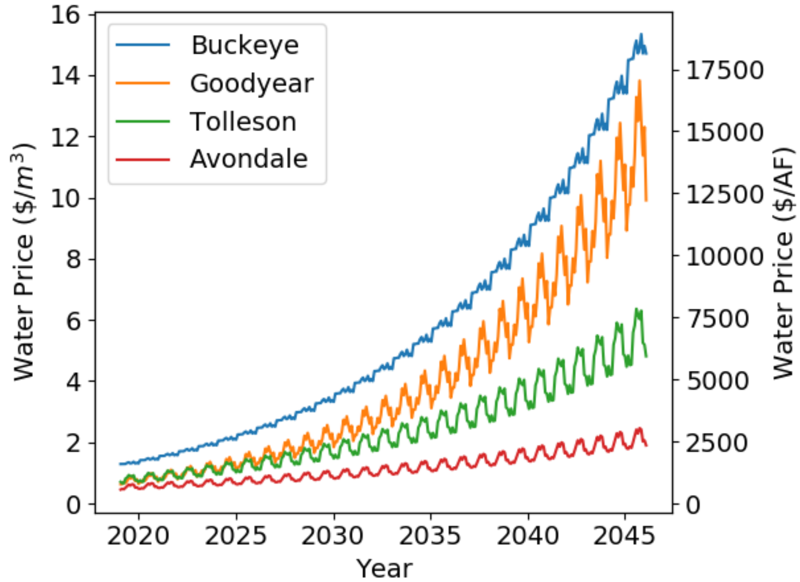


Figure 51. Projected water price by municipality. Analysis is for an RO2 with a size of 1.2e6 m^3/yr (1000AF/yr), the smallest regional RO in this analysis.

Now assume a bigger regional RO that can satisfy (at least for some time) the demand for one or more municipalities. Water is still distributed proportionally to all municipalities according to their population as in the case of the small RO2, but as soon as demand for one municipality is satisfied, the excess water is distributed to the remaining municipalities (again proportional to their population) until demand for all municipalities is satisfied. After that, if there is still excess water, it is distributed (proportionally) to the municipalities for the price of water calculated using the supply and demand relationship set forth in Section 3.5. An example is shown in Figure 52 and Figure 53. In this case, one can see that in the near future (some years), the assumed regional RO in the example (arbitrary chosen at 2.3e7 m^3/yr (18600 AF/yr)) will satisfy the demand for all municipalities. Correspondingly, the water price is depressed for the month of overproduction. On the other hand, as soon as all water from the RO can be sold to the municipalities (after few years for the RO size shown in the example), the price becomes the same as for the previous example using the small RO (since we assume other water sources can cover the demand and no price elasticity is seen).

The first scenario assumes that all four municipalities buy water starting at the first year of sale. Each municipality buys a percentage of water proportional to its population. The LCOCT for this case is unaffected from the one calculated earlier in Section 4.2.1. The LCOCT considered in this case offsets all; i.e., the water treatment cost and effluent water cost saving at APS. Instead of computing the LCOPW for RO2 as before, the resulting NPV of the regional RO system using the water market prices is shown in Figure 54. The NPV increases as regional RO size increases. As one can see, the regional RO is not profitable only for very small regional RO sizes (<2.5e6 m^3/yr (2000 AF/yr)) in combination with relatively large RO1 systems (>4% slip stream). In this region, the LCOPW is higher than the market price. Figure 55 shows, for the same scenario, the IRR for RO2. One can see that it plateaus at ~25%.

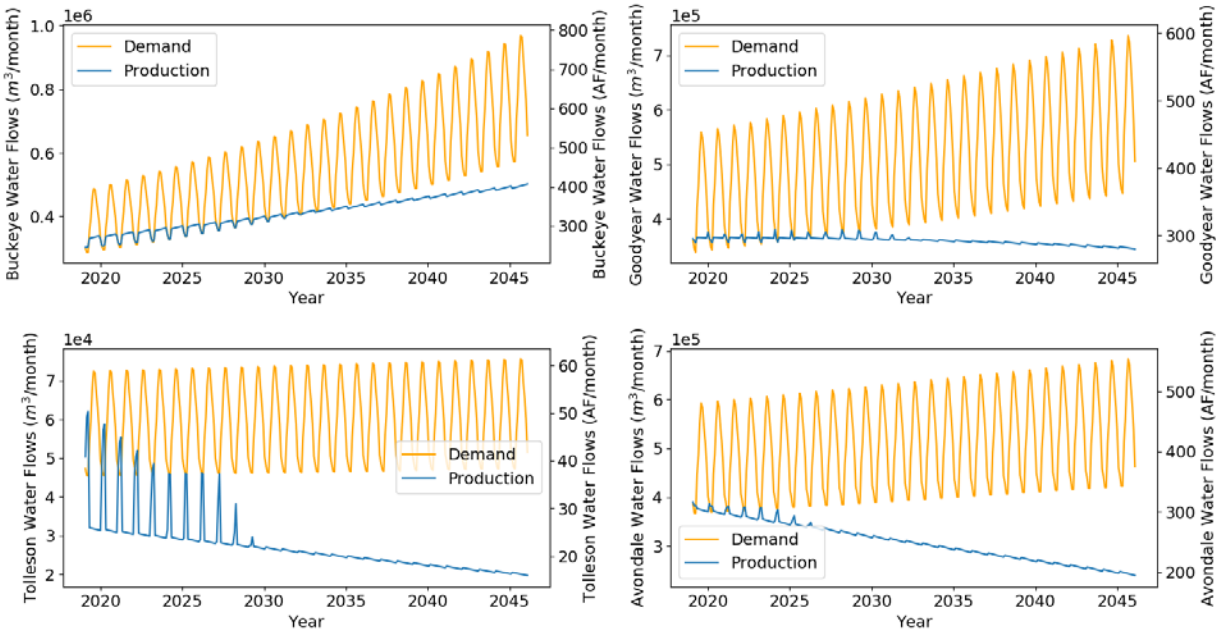


Figure 52. Projected water demand and regional RO production by municipality. Analysis is for an RO2 with a size of 2.3e7 m^3/yr (18600 AF/yr).

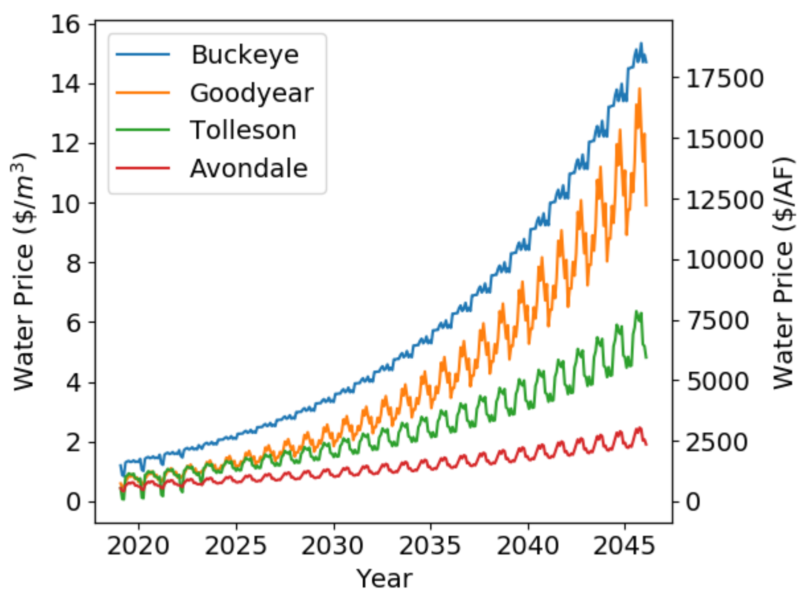


Figure 53. Projected water price by municipality. Analysis is for an RO2 with a size of 2.3e7 m^3/yr (18600 AF/yr).

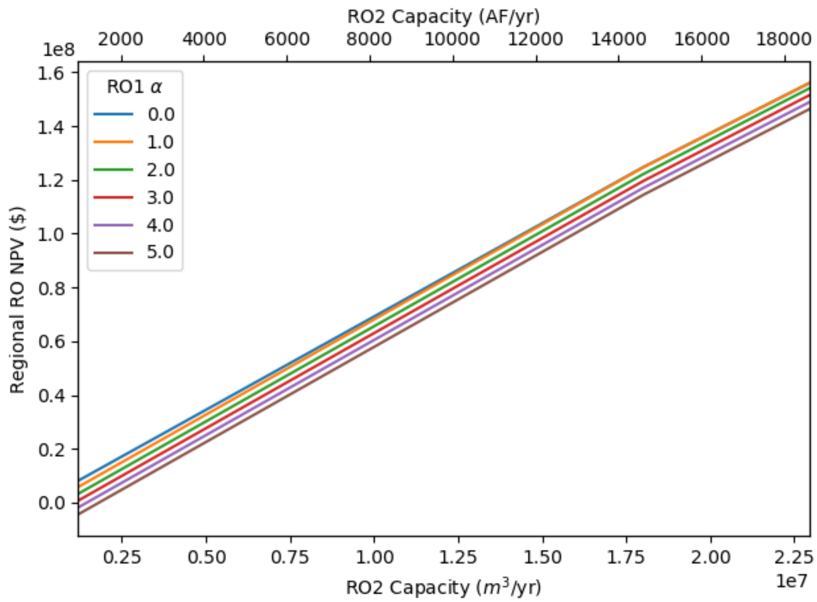


Figure 54. NPV of regional RO system vs its size for different RO1 sizes (different color lines). LCOCT considered in this case offsets water treatment cost and effluent water cost saving at APS. The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

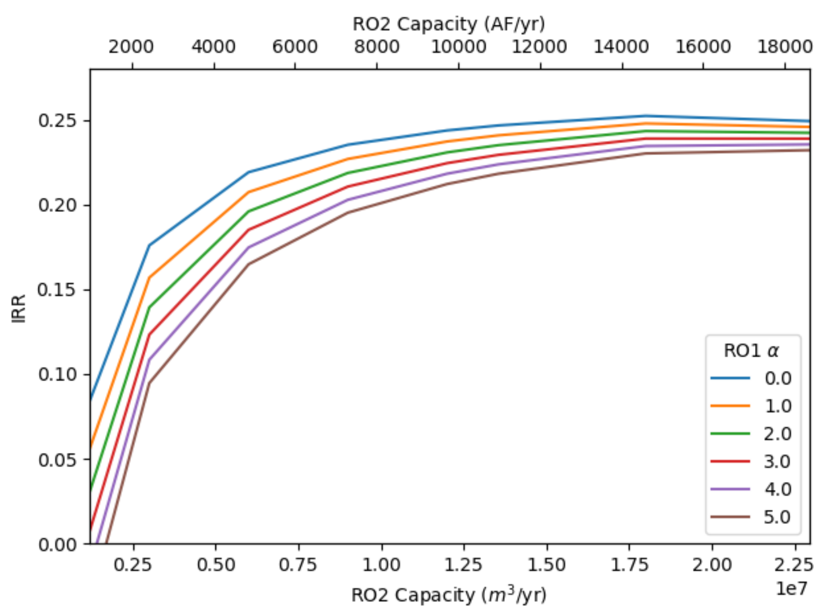


Figure 55. IRR of Regional RO system vs its size for different RO1 sizes (different color lines). LCOCT considered in this case offsets water treatment cost and effluent water cost saving at APS. The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

As discussed in Section 3.4.2, instead of separating the economics of APS and the regional RO, one can evaluate the economics of the global project. With that, if the global project is economically viable, the profit can be split between the participating stakeholders. Recall that even if the regional RO and APS are considered as one economic entity, they can still be two business entities. This gives a more general information compared to the two cases (LCOCT offsets water treatment cost only and LCOCT offsets all, water treatment cost and water acquisition savings) looked at previously, since any split of profit can be negotiated between APS and the regional RO. Figure 56 shows the difference in NPV between the CASE 0 and the global CASE 1; i.e., this is the total profit. One can see that the global delta NPV is the same as the NPV of RO2 only (see Figure 54). This means that the concentrate treatment cost is exactly offset by the water acquisition and treatment cost at APS and all of the profit is made by RO2. This is expected, since the LCOCT considered for the results in Figure 54 is computed to offset all water acquisition and treatment cost at APS. For illustration, Figure 57 shows the global delta NPV for the case where no additional brackish water is injected into the WRSS. One can see that for this case, delta NPV is positive for somewhat bigger sizes of RO2 compared to the previous case. This is because APS has to purchase more expensive effluent water to offset the missing brackish water, which lowers the overall profit. Both cases considered indicate that the local water market and its projection in the future suggest building a regional RO2 is economically viable.

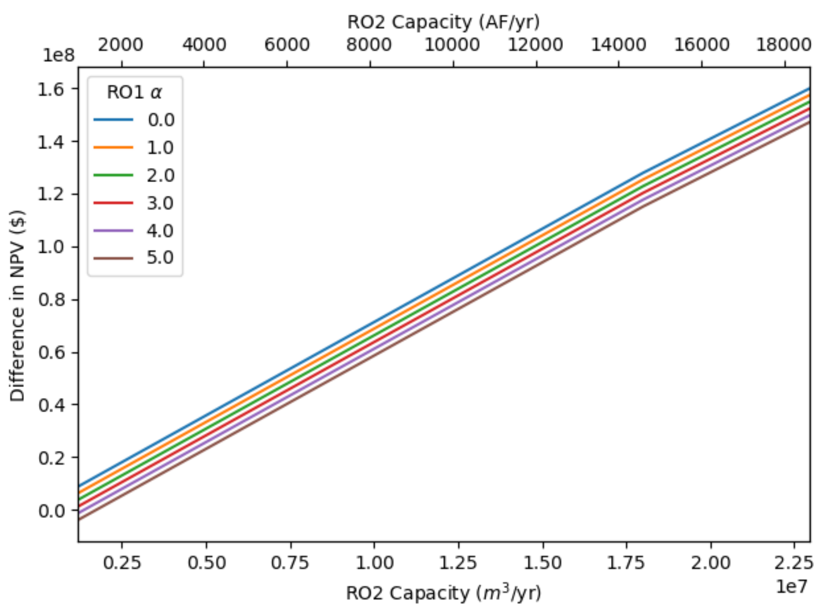


Figure 56. Delta NPV (CASE 0 and CASE 1) for the global project (APS and regional RO combined). The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

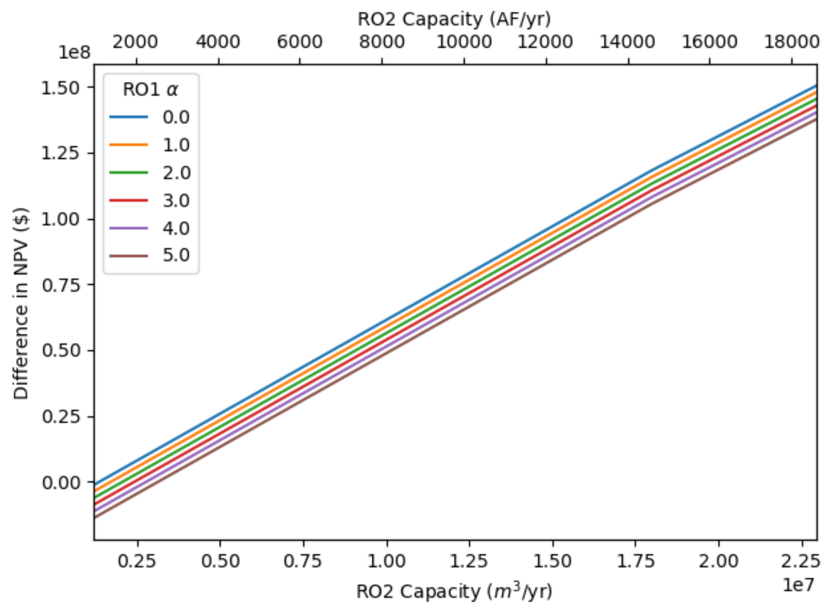


Figure 57. Delta NPV (CASE 0 and CASE 1) for the global project (APS and regional RO combined). The brackish water directly into the WRSS is set to 0 m^3/yr (0 AF).

4.2.4.2 Municipalities begin purchasing water from the regional RO at 5-year intervals

The second analysis assumes that the different municipalities come in at 5-year intervals. The order and year at which the municipalities start buying water from regional RO is in Table 18.

Table 18: Years When Municipality Starts Buying from Regional RO.

Municipality	Model Year	Actual Year
Buckeye	0	2019
Goodyear	5	2024
Tolleson	10	2029
Avondale	15	2034

The projected yearly demand for each municipality when they come in at 5-year intervals is plotted in Figure 58. The same initial population and assumed population growth rate as for the previous case is assumed (see Table 17).

As for the previous case where all municipalities start purchasing water from the beginning, if potable water produced in the regional RO is less than the projected monthly demand for each municipality, meaning that the regional RO produces less than the municipalities' consumption, the water is sold to all municipalities proportional to their respective population. On the other hand, when a bigger regional RO can satisfy (at least for some time) the demand for one or more municipalities, water is still distributed proportionally to all municipalities according to their population as in the case of the small RO2, but as soon as demand for one municipality is satisfied, the excess water is distributed to the remaining municipalities (again proportional to their population) until demand for all municipalities is satisfied. After that, if there is still excess water, it is distributed (proportionally) to the municipalities for the price of water calculated using the supply and demand relationship set forth in Section 3.5. An example when municipalities come in at 5-year intervals is shown in Figure 59 and Figure 60. In this case, one can see that the assumed regional RO in the example (arbitrary chosen at 2.3e7 m^3/yr (18600 AF/yr)) will satisfy the demand for all municipalities for some time in the future. Correspondingly, the water price is depressed (down to zero) for the periods of overproduction.

In the same manner as for the previous case where all municipalities participated from the beginning, Figure 61 to Figure 64 show the economics of RO2 and the global project when the municipalities come in at 5-year intervals. Contrary to the previous case, the NPV of the regional RO2 as well as the global NPV show a plateau for RO2 sizes bigger than ~2.0e7 m^3/yr (16000 AF/yr). Bigger RO2s seem not to increase profit, since they saturate the water market for a long time in the first years, collapsing the water price.

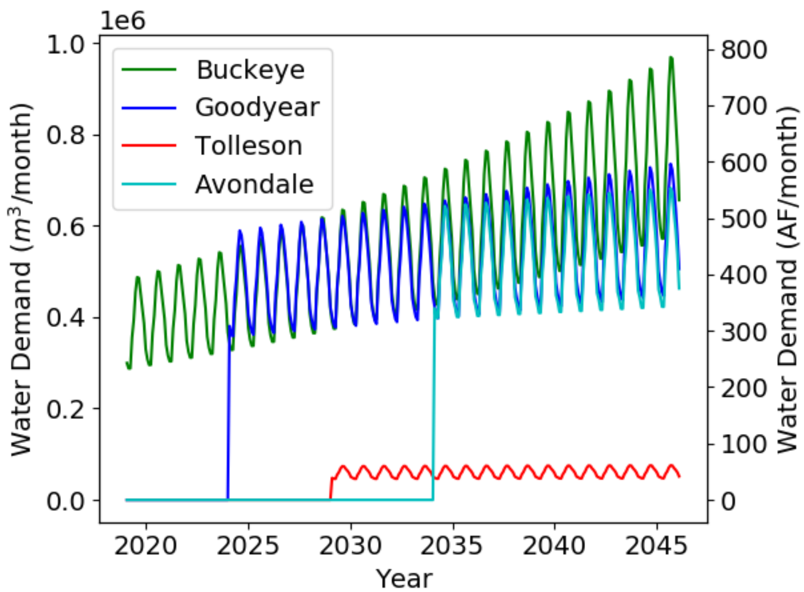


Figure 58. Municipality water demand growth projection. One municipality begins purchasing Regional RO water every 5 years.

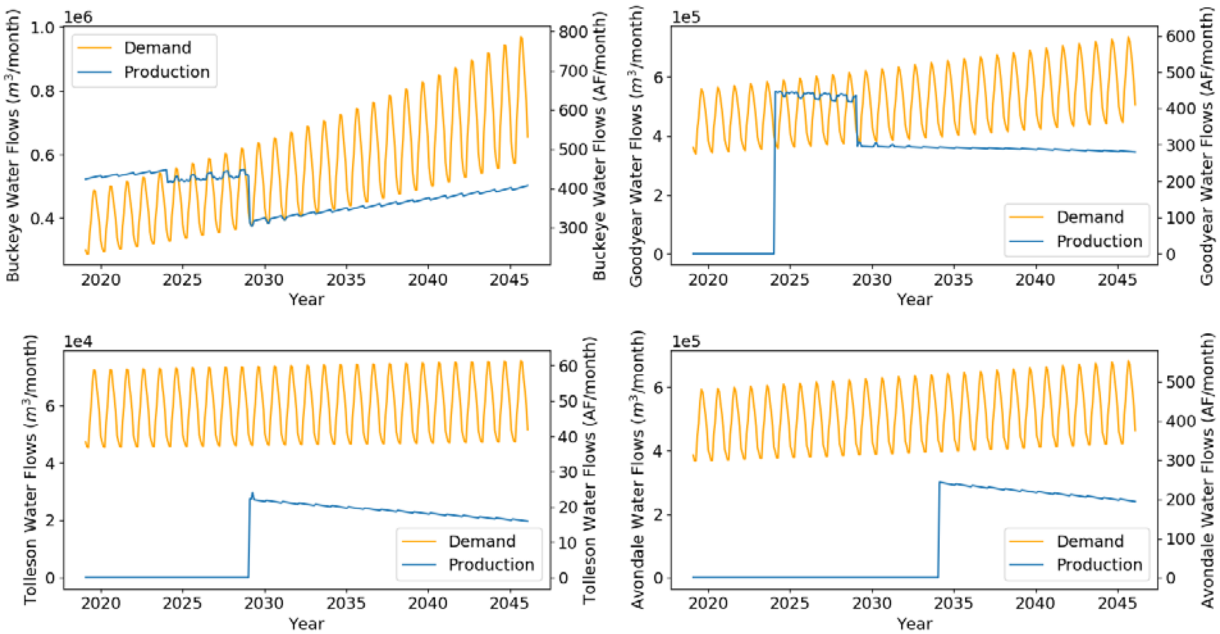


Figure 59. Projected water demand and regional RO production by municipality. Analysis is for an RO2 with a size of 2.3e7 m^3/yr (18600 AF/yr), the largest regional RO in this analysis. One municipality begins purchasing Regional RO water every 5 years.

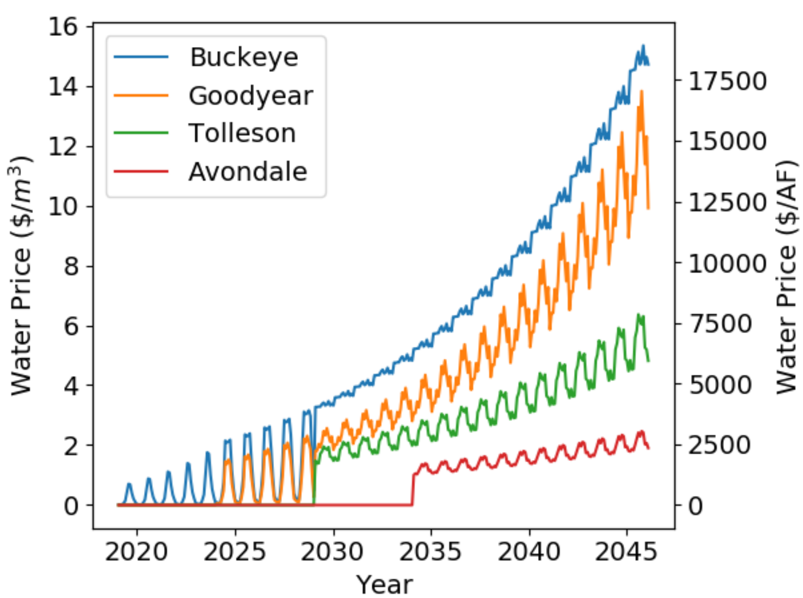


Figure 60. Projected water price by municipality. Analysis is for an RO2 with a size of 2.3e7 m^3/yr (18600 AF/yr), the largest regional RO in this analysis. One municipality begins purchasing Regional RO water every 5 years.

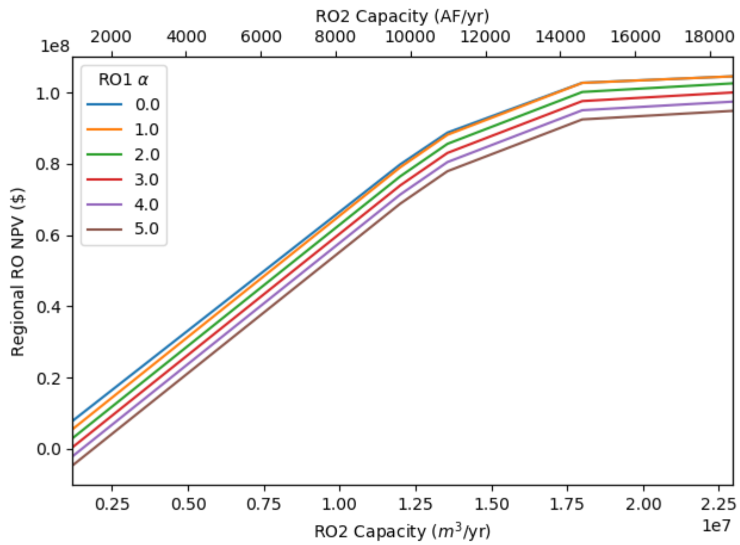


Figure 61. NPV of regional RO system vs it's size for different RO1 sizes (different color lines). LCOCT considered in this case offsets water treatment cost and effluent water cost saving at APS. The brackish water directly into the WRSS is set at the optimum found for CASE 0, i.e. 1.9e7 m^3/yr (15500 AF/yr).

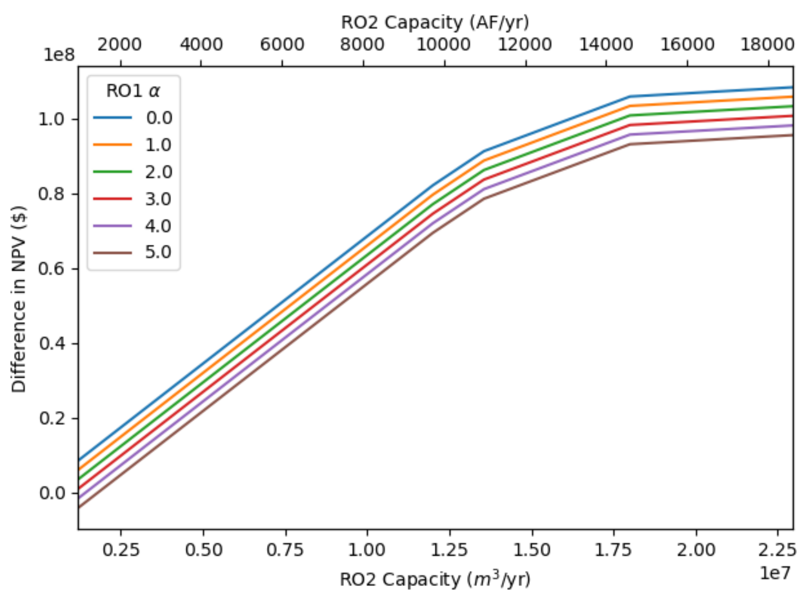


Figure 62. Delta NPV (CASE 0 and CASE 1) for the global project (APS and regional RO combined). The brackish water directly into the WRSS is set at the optimum found for CASE 0, i.e. 1.9e7 m^3/yr (15500 AF/yr).

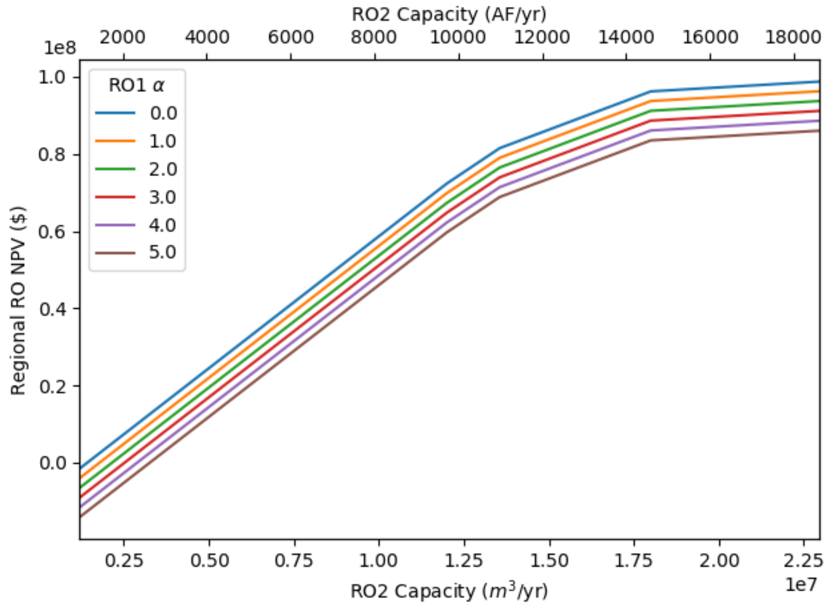


Figure 63. NPV of regional RO system vs it's size for different RO1 sizes (different color lines). LCOCT considered in this case offsets water treatment cost and effluent water cost saving at APS. The brackish water directly into the WRSS is set at 0 m^3/yr (0 AF/yr).

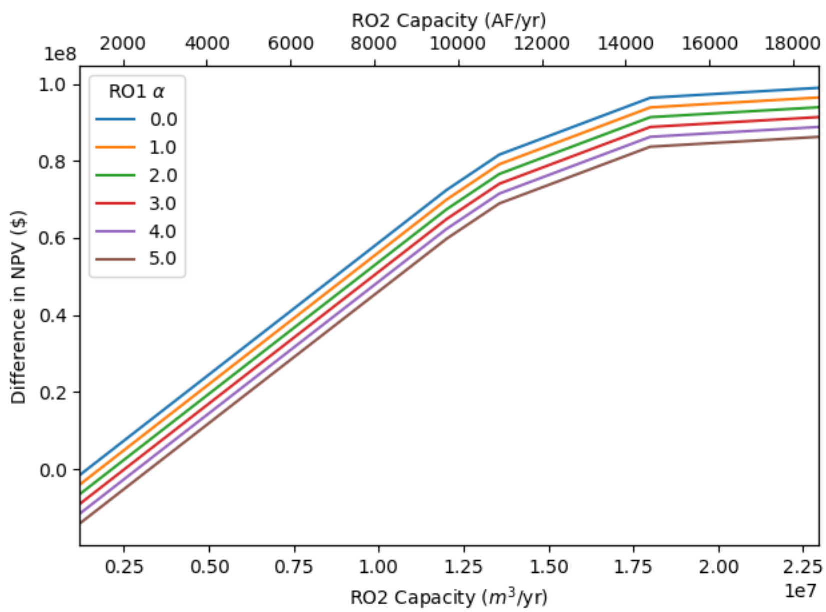


Figure 64. Delta NPV (CASE 0 and CASE 1) for the global project (APS and regional RO combined). The brackish water directly into the WRSS is set at 0 m^3/yr (0 AF/yr).

5. CONCLUSIONS AND FUTURE WORK

This section provides a summary of the conclusions drawn from the analysis results and provides recommendations for potential future work.

5.1 Conclusion

This report presents a techno-economic study that investigates the economic viability of a large-scale RO desalination plant in the west valley area of Phoenix. In addition to providing potable water for the adjacent municipalities, the concentrate from the regional RO plant would be taken and treated by the PVGS to provide some cooling water for a (hopefully) lower cost than that of the municipal effluent water.

The problem to solve has three main degrees of freedom:

- The amount of brackish water sent into the regional RO; i.e., RO2 size.
- The percentage of WRF outlet water treated by RO1 (slip stream designated as α); i.e., RO1 size.
- The amount of brackish water directly injected into the WRSS.

Ranges for the degrees of freedom have been investigated to show impact on the problem's economics as well as to find optimal (most profitable) combinations of RO sizes. Separate effects for each of the three degrees of freedom have been discussed in the report. Figure 65 to Figure 68 summarize and link the findings for the case where water market is not considered and the LCOCT and LCOPW are computed. The figures show the LCOCT and LCOPW (color map) as a function of RO1 and RO2 size for 0 m^3/yr (0 AF/yr) and 1.9e7 m^3/yr (15500 AF/yr) of brackish water directly injected in the WRSS. Furthermore, the color maps are shown for the case where LCOCT offsets water treatment cost and water acquisition savings, as well as for the case where LCOCT only offsets water treatment cost. The plots include the physical limits of the system; i.e., the restriction on the maximum blowdown permissible for the current evaporation ponds (4.38e6 m^3/yr (3550 AF/yr)) and the salinity operational target (450 ppm) in the reservoir ponds (assuring cooling water quality for the RPS).

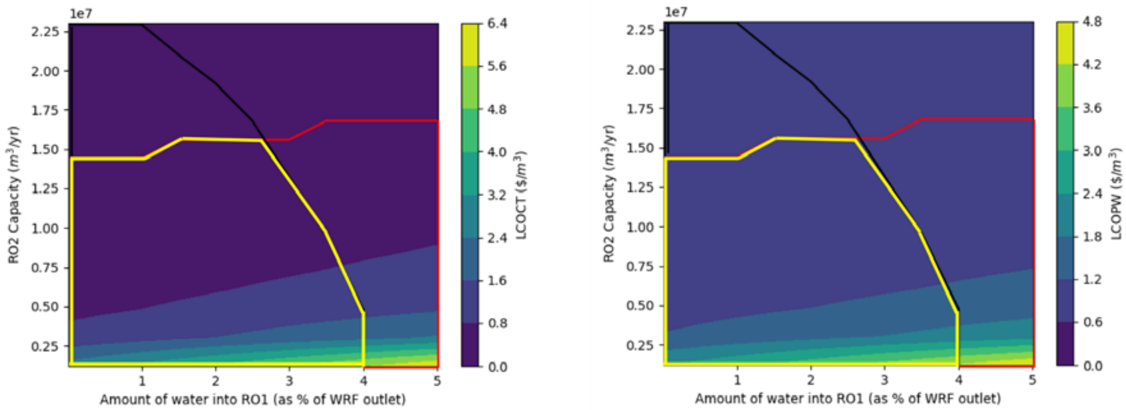


Figure 65. LCOCT and LCOPW as a function of RO1 and RO2 capacity. The brackish water directly into the WRSS is to 0 m^3/yr (0 AF/yr). The LCOCT in this case offsets the water treatment cost as well as the effluent acquisition savings for APS. The red box represents the region for which the chloride concentration in the reservoir ponds is below 450 ppm. The black box represents the region for which the total blowdown is under 4.38e6 m^3/yr (3550 AF/yr). The yellow box shows the region for which both, the salinity and the blowdown limits are respected.

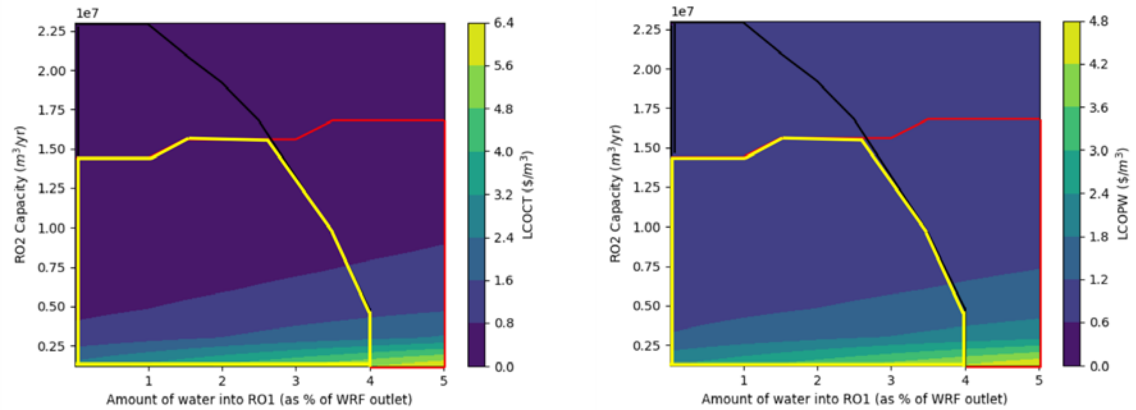


Figure 66. LCOCT and LCOPW as a function of RO1 and RO2 capacity. The brackish water directly into the WRSS is to 0 m^3/yr (0 AF/yr). The LCOCT in this case offsets only the water treatment cost for APS. The red box represents the region for which the chloride concentration in the reservoir ponds is below 450 ppm. The black box represents the region for which the total blowdown is under 4.38e6 m^3/yr (3550 AF/yr). The yellow box shows the region for which both, the salinity and the blowdown limits are respected.

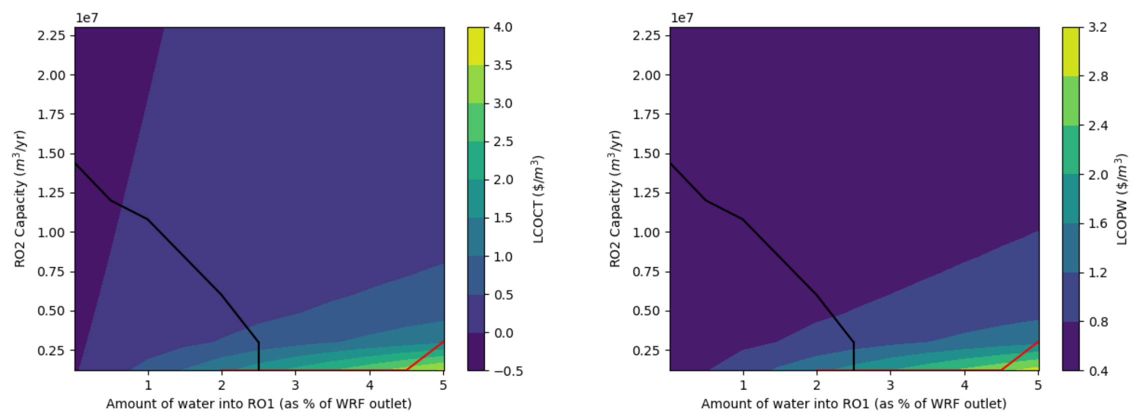


Figure 67. LCOCT and LCOPW as a function of RO1 and RO2 capacity. The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The LCOCT in this case offsets the water treatment cost as well as the effluent acquisition savings for APS. The area under the red line represents the region for which the chloride concentration in the reservoir ponds is below 450 ppm. The black box represents the region for which the total blowdown is under 4.38e6 m^3/yr (3550 AF/yr). There is no overlap, i.e. no combination of RO1 and RO2 size that respects both constraints simultaneously.

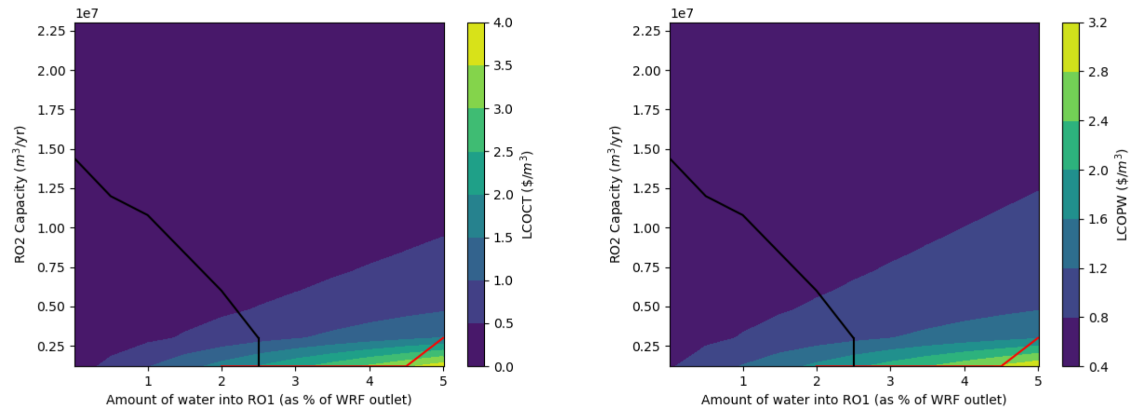


Figure 68. LCOCT and LCOPW as a function of RO1 and RO2 capacity. The brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr). The LCOCT in this case only offsets the water treatment for APS. The area under the red line represents the region for which the chloride concentration in the reservoir ponds is below 450 ppm. The black box represents the region for which the total blowdown is under 4.38e6 m^3/yr (3550 AF/yr). There is no overlap, i.e. no combination of RO1 and RO2 size that respects both constraints simultaneously.

In addition, the multidimensional color plots are also shown (see Figure 69) for the case where the LCOPW is not computed, but the water prices from the water market model are used. In this case, the figures show the delta NPV (CASE 0 compared to CASE 1) as a function of RO1 and RO2 size for the case where all four municipalities start buying water from the regional RO in the first year of production. Like before, also here two cases are presented; 0 m^3/yr (0 AF/yr) and 1.9e7 m^3/yr (15500 AF/yr) of brackish water directly injected in WRSS.

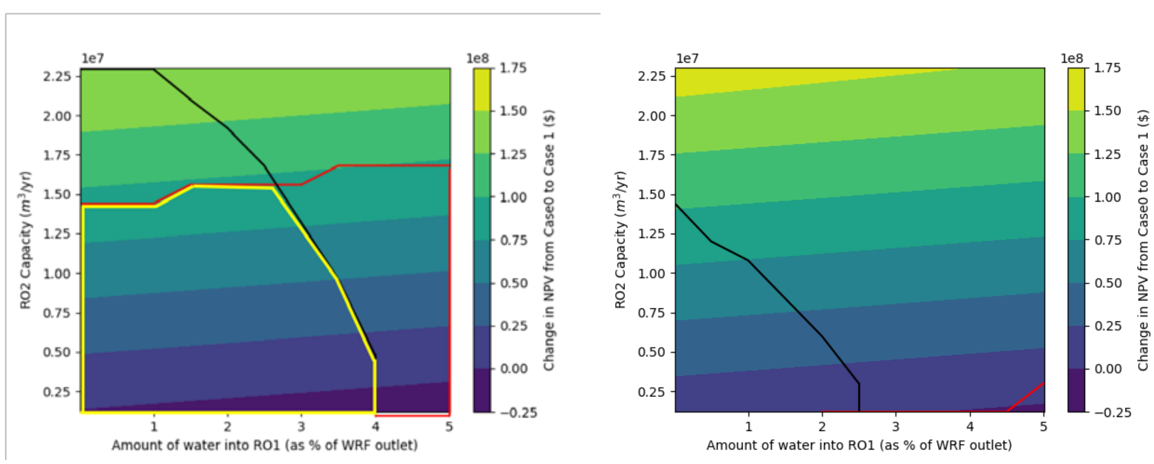


Figure 69. Delta NPV (between CASE 0 and CASE 1) as a function of RO1 and RO2 capacity. The area under the red line represents the region for which the chloride concentration in the reservoir ponds is below 450 ppm. The black box represents the region for which the total blowdown is under 4.38e6 m^3/yr (3550 AF/yr). **Left**) the brackish water directly into the WRSS is set to zero; **Right**) the brackish water directly into the WRSS is set at the optimum found for CASE 0; i.e., 1.9e7 m^3/yr (15500 AF/yr).

In general, the study shows that there exist combinations of regional RO and PVGS RO sizes for which the total blowdown and water chemistry limits at PVGS (including regional RO concentrate treatment at PVGS either through increased blowdown or onsite RO treatment) are satisfied. However, possible combinations only exist if no additional brackish water is directly mixed into the tertiary system at PVGS. The lowest LCOPW (~0.5 $/m^3) can be achieved with a size of the regional RO of ~1.4e7 m^3/yr (11000 AF/yr) capacity, which leads to ~8.63e6 m^3/yr (7000 AF/yr) of potable water while no onsite RO at PVGS is built. Or, considering the residential water demand model developed for the Phoenix west valley, the NPV of the regional RO respecting the physical constraints would be ~$100 million if all municipalities in the vicinity participate from the beginning of the project. The maximum size regional RO respecting the physical boundary conditions can be achieved when no additional brackish water is directly mixed in the tertiary system at PVGS and a PVGS onsite RO of ~2.3% slipstream is built. The corresponding regional RO size is 1.5e7 m^3/yr (12500 AF/yr), which is only slightly bigger than the regional RO with the lowest LCOPW (within the physical boundaries). However, the LCOPW for that biggest regional RO is slightly less favorable compared to the case where no RO1 is built. The developed water marked model suggests that bigger regional ROs (beyond 11000 AF/yr) will be even more profitable. However, to dispose of the concentrate of larger regional ROs at PVGS, additional evaporation ponds will have to be constructed. This cost was not considered in the present study.

From the summary figures and the detailed figures in the main body of the report, it has been shown that:

***For CASE 0*, Existing Palo Verde configuration – Maximum brackish water without supplemental RO treatment**

- Considering only the blowdown limit for the evaporation ponds (4.38e6 m^3/yr (2200 gpm, 3550 AF/yr)), a brackish water input of approximately 3.6e7 m^3/yr (29000 AF/yr) will cause the cooling system to exceed that limit when there are no ROs in the system. The corresponding chloride concentration in the reservoir is ~550 ppm. Recall that all reported chloride concentrations are yearly time-averages, not maximums.
- Considering only the chloride concentration constraint in the reservoir pond (450 ppm), a brackish water input of approximately 1.9e7 m^3/yr (15500 AF/yr) reaches that limit. The chloride concentration constraint is the more conservative limit compared to the blowdown limit.
- The partial NPV (i.e., the discounted cooling water acquisition and treatment cost at APS for the case no ROs are built) is highest if no brackish water is purchased; partial NPV would be decreasing with increasing brackish water amounts blended into the WRSS.
- For the more-restrictive case (450 ppm chloride concentration in reservoir ponds); i.e., for 1.9e7 m^3/yr (15500 AF/yr) of brackish water blended into the WRSS (still no ROs are built), the partial NPV for the cooling water is ~ $ 94 million.

For CASE 1, RO1 and RO2 are both built

Physical system constraints

- For a given total blowdown limit (cooling tower and onsite RO1), the maximum salinity in the reservoir can be higher (i.e. a larger RO2 can be built) when the water is run through the cooling tower (with fewer cycles) and blown down to the evaporation ponds, compared to desalination with an onsite RO. This is because the reduction in blowdown from the circulating water system by having an onsite RO (lower salinity water in cooling loop) is lower compared to the concentrate produced from the onsite RO1. In other words, for a given total blowdown limit, the circulating water system blowdown is more efficient in chloride reduction in the loop than the RO1. This conclusion only considers the blowdown limit and not the associated economics.

- Without building RO1, the maximum size RO2 that can be built, staying only within the blowdown limit (but violating the salinity constraint), is 1.4e7 m^3/yr (11000 AF/yr), when in addition 1.9e7 m^3/yr (15500 AF/yr) brackish water are injected directly in the WRSS. That corresponds to ~8.63e6 m^3/yr (7000 AF/yr) of potable water produced. The corresponding reservoir salinity is ~ 530 ppm. The maximum RO2 size grows to 2.8e7 m^3/yr (23000 AF/yr) if no additional brackish water is injected into the WRSS. This corresponds to ~1.7e7 m^3/yr (14000 AF/yr) of potable water produced. However, the corresponding reservoir salinity is above 450 ppm.
- To stay within 450 ppm salinity in the reservoir (for 1.9e7 m^3/yr (15500 AF/yr) brackish water injected directly in the WRSS), an RO1 of at least 3% slip stream needs to be built, which produces more blowdown than the allowable limit even if no regional RO is built.
- For the blowdown constraint only, the maximum RO2 size possible is decreasing with increasing RO1 size. On the other hand, for the salinity constraint, the maximum RO2 size possible is increasing with increasing RO1 size. The optimum size of RO1 is ~ 2.3% slipstream, which leads to a maximum size RO2 of 1.5e7 m^3/yr (12500 AF/yr) not violating both physical constraints (blowdown and salinity), in case no additional brackish water is injected in the WRSS. For reference, the size of RO2 not violating both physical constraints (blowdown and salinity), in case no additional brackish water is injected in the WRSS and no RO1 is built is very close, i.e. ~1.4e7 m^3/yr (11000 AF/yr).
- Considering these results, to be able to build RO2s bigger than 1.5e7 m^3/yr (12500 AF/yr), one of the constraints needs to be lifted; i.e., either additional evaporation ponds need to be built to allow for more blowdown, or the RPS plant needs to be adjusted to be able to accept higher salinity water for cooling. In addition, assuming higher efficiencies for the RO plants will likely change this picture as well.

No water market: LCOCT and LCCPW

- First, the case where the LCOCT offsets the water treatment cost and in addition, also propagates the effluent water cost savings to the owner/operator of RO2 is discussed.
    - As the size of the regional RO increases, the LCOCT decreases. This is because the concentrate offsets the need for effluent water, reducing the overall water acquisition cost at APS.
    - The LCOCT is also a function of RO1 size. Since a bigger RO1 will lead to more water consumption (more concentrate from RO1), the water cost will rise and so will the LCOCT.
    - The water acquisition and treatment cost may be larger in CASE 0 compared to CASE 1 for some cases with a small RO1 or a big RO2; i.e., the savings in effluent water acquisition (considered over the project lifetime) outweighs the cost of building the onsite RO1 at PVGS. It that case, the LCOCT is negative. The analysis does not consider APS paying for RO2 concentrate, but rather sets the LCOCT to zero for these cases.
    - LCOPW shows the same behavior as LCOCT.
    - LCOPW flattens out at about 0.55 \$/m^3 in the regions where the LCOCT becomes zero.
    - LCOCT and, consequently, LCOPW decrease with the amount of brackish water directly injected into the WRSS, since more brackish water means less of the more expensive effluent water has to be purchased.
- Second, the case where the LCOCT offsets only the water treatment cost is discussed.

    For the case where 15500 AF/yr of brackish water are injected into the WRSS:

    - The LCOCT is somewhat higher ranging from 0.25 to 3.8 \$/m^3 for small RO2s compared to 0 to 3.5 \$/m^3 in the previous case where the LCOCT also offsets the water acquisition savings.

- The tangential cost of LCOCT for bigger RO2s is ~0.2 $/m^3 compared to negative (zero) values in the previous case where the LCOCT also offsets the water acquisition savings.
- The LCOPW ranges from 0.75 to 3.0 $/m^3 for small RO2s. Which is also somewhat higher compared to the previous case where the LCOCT also offsets the water acquisition savings. This corresponds to the increase in LCOCT between the cases.
- For large RO2s, LCOPW is ~0.7 $/m^3 compared to 0.6 $/m^3 in the previous case where the LCOCT also offsets the water acquisition savings. This indicates that the water treatment cost is about ~0.1 $/m^3 higher compared to the case where LCOCT offsets the water treatment cost and effluent water savings. To get an order of magnitude, the effluent water savings at APS, i.e. the difference on water cost between the two cases where LCOCT offsets all or only the water treatment cost would be (for a RO2 size of 1.4e7 m^3/yr (11000 AF/yr)) ~ 500,000 $/yr.

For the case where no additional brackish water are injected into the WRSS:

- The difference in LCOCT and LOCPW between the case where the LCOCT offsets only the water treatment costs and the case where the LCOCT also offsets the water acquisition savings vanishes. This indicates that the small savings in effluent water made in case brackish water is injected directly into the WRSS are reduced when no brackish water is injected. Remember that CASE 0 always includes 1.9e7 m^3/yr (15500 AF/yr) of brackish water injected into the WRSS. If for CASE 1, this direct injection is replaced by effluent water, the savings in its acquisition vanishes.

Water market: NPV and IRR

- From the water-demand model, the four municipalities need ~1.5e7 m^3/yr (12000 AF/yr) potable water now, which will rise to 2.1e7 m^3/yr (17000 AF/yr) by the end of the project.
- The NPV increases as regional RO size increases if all municipalities join the project from the beginning. The regional RO is not profitable only for very small regional RO sizes (<2.5e6 m^3/yr (2000 AF/yr)), in combination with relatively large RO1 systems (>4% slip stream). In this region, the LCOPW is larger than the market price. Considering the IRR for RO2, it plateaus out at ~25% for big RO2s.
- If the municipalities come in at a 5-year interval, contrary to the previous case, the NPV of the regional RO as well as the global NPV show a plateau for RO2 sizes bigger than ~2.0e7 m^3/yr (16000 AF/yr). Bigger RO2s seem not to increase profit, since they saturate the water market for a long time in the first years, collapsing the water price.

Economic sensitivities

- Varying the APS and RO2 discount rate between 5 and 15% leads to approximately ±45% difference in LCOCT and consequently the same difference in LCOPW.
- Considering a 20-year life extension for PVGS lowers the LCOCT by ~7% and, consequently, the LCOPW by ~4%.
- Varying the wholesale electricity price has no impact, as it cancels out in the differential analysis.

5.2 Future Work

Future work is suggested in the following areas:

- Uncertainties should be added to all inputs. In particular, the capex for the ROs, as well as the growth rate and water prices for the considered municipalities, should include uncertainties. With these, bands of LCOCT, LCOPW, NPV and IRR can be presented. Investigating the sensitivities around growth rates is especially essential; the fastest growing city in the United States is Buckeye, AZ, a city in the study area. Further, the U.S. Census Bureau places Phoenix as the fifth largest city in the country. These combined facts underscore the applicability of this analysis for planners interested to sure-up the region's long-term water supply.

- Investigate different water desalination technologies or RO membranes with different efficiencies. If a cost can be attached to the efficiency of the desalination process, water desalination cost can be compared to building more evaporation ponds. As mentioned, for the applied RO plant efficiency, it is always beneficial to evaporate the water instead of using RO technology to purify and re-use the water. This conclusion could change for more efficient ROs depending on their cost.
- This study adopts a specified perspective to conduct the analysis. In future work varying perspectives could inform on how different stakeholders might view the RO project. For example, municipal water utilities may generate financial benefits (or additional costs) by purchasing the regional RO's water. As the regional RO's water supply adds to the water portfolio for municipalities, a benefit not yet computed is the value of preserving current stocks of water to use as buffers in times of extreme drought. Considerations such as this example will likely shed light, in a quantitative, monetized way, on how the project benefits local municipalities.

6. REFERENCES

1. A. Epiney, C. Rabiti, P. Talbot, J. S. Kim, J. Richards, S. Bragg-Sitton, "Case Study: Nuclear-Renewable-Water Integration in Arizona," Idaho National Laboratory, September 2018, INL/EXT-18-51359.
2. P. Talbot, P. Burli, J. Richards, A. Epiney, M. Abdo, C. Rabiti, R. Boardman, "Analysis of differential financial impact of LWR load-following operations," Idaho National Laboratory, September 2019, INL/EXT-19-55614.
3. www.google.com/maps
4. C. Rabiti, H. E. Garcia, R. Hovsapian, R. A. Kinoshita, G. L. Mesina, S. M. Bragg-Sitton, R. D. Boardman, "Strategy and Gaps for Modeling, Simulation, and Control of Hybrid Systems," Idaho National Laboratory, April 2015, INL/EXT-15-34877.
5. A. S. Epiney, J. Chen, C. Rabiti, "Status on the Development of a Modeling and Simulation Framework for the Economic Assessment of Nuclear Hybrid Energy Systems (FY 16)," Idaho National Laboratory, September 2016, INL/EXT-16-39832.
6. A. S. Epiney, R. A. Kinoshita, J. S. Kim, C. Rabiti, M. S. Greenwood, "Software development infrastructure for the HYBRID modeling and simulation project," Idaho National Laboratory, September 2016, INL/EXT-16-40004.
7. A. S. Epiney, C. Rabiti, A. Alfonsi, P. Talbot, F. Ganda, "Report on the Economic Optimization of a Demonstration Case for a Static N-R HES Configuration using RAVEN," Idaho National Laboratory, April 2017, INL/EXT-17-41915.
8. C. Rabiti, A. S. Epiney, P. Talbot, J. S. Kim, S. Bragg-Sitton, A. Alfonsi, A. Yigitoglu, S. Greenwood, S. M. Cetiner, F. Ganda, G. Maronati, "Status Report on Modeling and Simulation Capabilities for Nuclear-Renewable Hybrid Energy Systems," Idaho National Laboratory, September 2017, INL/EXT-17-43441.
9. R. Ponciroli and R. B. Vilim, "Testing of Strategies for the Acceleration of the Cost Optimization," Argonne National Laboratory, August 2017, ANL/NE-17/21.
10. M.S. Greenwood, S.M. Cetiner, T.J. Harrison, D. L. Fugate, "A Templated Approach for Multi-Physics Modeling of Hybrid Energy Systems in Modelica." (In Press)
11. C. Rabiti, A. Alfonsi, J. Cogliati, D. Mandelli, R. Kinoshita, S. Sen, C. Wang, J. Chen, "RAVEN User Manual," Idaho National Laboratory, March 2017, INL/EXT-15-34123.
12. A. Alfonsi, C. Rabiti, D. Mandelli, J. Cogliati, R. Kinoshita, and A. Naviglio,"RAVEN and Dynamic Probabilistic Risk Assessment: Software Overview," in *Proceedings of European Safety and Reliability Conference (ESREL)*, Wroklaw (Poland), 2014.
13. A. Alfonsi, C. Rabiti, D. Mandelli, "RAVEN Facing the Problem of Assembling Multiple Models to Speed Up the Uncertainty Quantification and Probabilistic Risk Assessment Analyses," Proceedings of *13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)*, 2-7 October, 2016, Seoul, South Korea.
14. B. S. Garbow," MINPACK-1, Subroutine Library for Nonlinear Equation System," Organisation for Economic Co-Operation and Development, Nuclear Energy Agency - OECD/NEA, 25 April 1984, Le Seine Saint-Germain, France.
15. J. S. Kim and H. E. Garcia, "Nuclear-Renewable Hybrid Energy System for Reverse Osmosis Desalination Process," Transactions of the American Nuclear Society, 2015, 112:121-4.
16. J. S. Kim, J. Chen J, H. E. Garcia, "Modeling, control, and dynamic performance analysis of a reverse osmosis desalination plant integrated within hybrid energy systems," *Energy*, 2016, 112, 52-66.
17. J. S. Kim, K. Frick, "Status Report on the Component Models Developed in the Modelica Framework: Reverse Osmosis Desalination Plant & Thermal Energy Storage," Idaho National Laboratory, October 2016, INL/EXT-18-45505.
18. L. F. Greenlee, D. F. Lawler, B. D. Freeman, B. Marrot, P. Moulin, "Reverse osmosis desalination: Water sources, technology, and today's challenges," *Water Research*, 2009, 43,

2317-48.
19. H. E. Garcia, J. Chen, J. S. Kim, M. G. McKellar, W. R. Deason, R. B. Vilim, et al., "Nuclear Hybrid Energy Systems – Regional Studies: West Texas & Northeastern Arizona," Idaho National Laboratory, April 2015, INL/EXT-15-34503.
20. H. E. Garcia, J. Chen, J. S. Kim, R. B. Vilim, W. R. Binder, S. M. Bragg Sitton, et al., "Dynamic performance analysis of two regional Nuclear Hybrid Energy Systems," *Energy*, 2016, 107, 234-58.
21. P. Fritzson. Principles of Object-Oriented Modeling and Simulation with Modelica 3.3: A Cyber-Physical Approach, 2nd ed., New Jersey, Wiley, 2014.
22. Dassault Systems. DYMOLA Systems Engineering, available at https://www.3ds.com/products-services/catia/products/dymola/, accessed on September 2018.
23. "2017 Monthly Chemisty.xlsx," APS private communication, June 2018.
24. "Cooling Demand and Cost.xlsx," APS private communication, June 2018.
25. "Cost Function for the Palo Verde Water Reclamation Facility_v2," APS private communication, August 2018.
26. https://new.azwater.gov/, accessed 28 August 2019.
27. https://data.bls.gov/cgi-bin/cpicalc.pl, accessed 28 August 2019.
28. https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-cities-and-towns.html, accessed 28 August 2019.
29. G. Noreddine, T. M. Missimer, G. L. Amy, "Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability," *Desalination*, 309 (2013), 197-207.
30. "160411 WRSS-Buckeye canal connection-JAB-R1.xlsx," APS private communication, May 2018.
31. "Tertiary PPM.xlsx," APS private communication, June 2018.
32. "Model Data - 1_SEND.XLSX," APS private communication, June 2018.
33. "Palovrde_asr_apnd_010116_123116_v1091917.xlsx," APS private communication, June 2018.
34. "2017 - 1.1 to 8.31 LMP 5 min at PV Hub.xlsx," APS private communication, June 2018.
35. "18D2686 Sample2COC Rev FINAL 05 07 18 1535.pdf," APS private communication, June 2018.
36. "4 season rep for Justin.xlsx," APS private communication, June 2018.