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Evaluating options for balancing the water–electricity nexus in California: Part 2—Greenhouse gas and renewable energy utilization impacts

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HIGHLIGHTS

- Part I presents a spatially and temporally resolved model of California's surface reservoirs.
- Part II presents GHG emissions and grid renewable penetration for water availability options.
- In particular, the energy signature of water supply infrastructure is delineated.
- Different pathways for securing California's water supply are developed quantitatively.
- Under baseline conditions, portfolios capable of securing surface reservoir levels emerge.
- Under climate change conditions, the water supply must be carefully selected to allay emissions.

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ABSTRACT

A study was conducted to compare the technical potential and effectiveness of different water supply options for securing water availability in a large-scale, interconnected water supply system under historical and climate-change augmented inflow and demand conditions. Part 2 of the study focused on determining the greenhouse gas and renewable energy utilization impacts of different pathways to stabilize major surface reservoir levels. Using a detailed electric grid model and taking into account impacts on the operation of the water supply infrastructure, the greenhouse gas emissions and effect on overall grid renewable penetration level was calculated for each water supply option portfolio that successfully secured water availability from Part 1. The effects on the energy signature of water supply infrastructure were found to be just as important as that of the fundamental processes for each option. Under historical (baseline) conditions, many option portfolios were capable of securing surface reservoir levels with a net neutral or negative effect on emissions and a benefit for renewable energy utilization. Under climate change augmented conditions, however, careful selection of the water supply option portfolio was required to prevent imposing major emissions increases for the system. Overall, this analysis provided quantitative insight into the tradeoffs associated with choosing different pathways for securing California's water supply.

1. Introduction and Background

Concerns about climate effects on water availability combined with increasing demands in various regions are driving interest in diversifying the water supply portfolio. Many regions in the world are expected to exhibit decreased water availability due to the impacts of climate change on regional hydrology and weather patterns (Boithias et al., 2014; Charlton and Arnell, 2011; Li et al., 2010; López-Moreno et al., 2014; Olmstead, in press; Pingale et al., 2014; Vairavamoorthy et al., 2008). A number of relevant studies have been performed for the water supply system of California in particular, due to its particular susceptibility to climate change impacts on water supply availability. Connell-Buck et al. (2011), Zhu et al. (2005), Tanaka et al. (2006), and Lund et al. (2003) investigated the effects of warmer and drier climates on water supply using the CALVIN model and outlined potential adaptation measures with respect to energy. Coupled with population growth and projected increases in demand in many regions, the need for more prudent water management strategies and options for usable water supply has been identified. However, reliance on the historical paradigm of precipitation-based and groundwater supplies may not be enough to meet increasing demands. Many alternative options for water supply

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are currently available, including but not limited to: urban water conservation, purification and reuse of treated wastewater, and desalination of seawater or brackish water using membrane or thermal processes. The accessibility of these options varies significantly by region, and their implications for water availability, energy usage, and greenhouse gas emissions depend strongly on the characteristics of a given region.

Certain aspects of the energy consumption and greenhouse gas impacts of different options to stabilize the water supply have been characterized. Many studies focus on the energy requirements of the fundamental physical processes and operation of associated facilities utilizing these options, and their subsequent economic impact.

Characterizing and reducing the energy consumption of desalination processes has been an active topic of interest. Al-Karaghouli and Kazmerski (2013) provided a review of the energy consumption of various desalination processes, with costs characterization using conventional and different renewable energy resources. Subramani et al. (2011) also outlined devices and novel technologies to minimize membrane desalination energy consumption, as well as a short discussion of renewable energy utilization. Kesieme et al. (2013) compared the economics of different seawater desalination processes in Australia in the context of available waste heat and materials costs, concluding that membrane desalination was the most cost effective option due to the lower cost materials, even with the presence of a carbon tax. Additionally, many studies have investigated the concepts for novel desalination plant and process configurations, including energy recovery and integration with dedicated renewable energy resources for reducing fossil fuel energy consumption and related emissions (Ong et al., 2012; Shaffer et al., 2012; Wang and Chung, 2012; Yılmaz and Söylemez, 2012; Al-Zahrani et al., 2012; Peñate and García-Rodríguez, 2011).

The energy and emissions footprint of water reuse has also been examined. The process energy consumption and diurnal behavior of water reuse processes (microfiltration, reverse osmosis, advanced oxidation) have been examined by Sobhani (2011), taking into account real-world plant operating constraints. An review of the energy intensity of water reuse and recovery was also given by Plappally and Lienhard (2012) for in-operation systems, ranging from between 0.33 and 1.86 kWh/m^3 depending on pumping requirements and system topography. Kajenthira et al. (2012) cite the lower energy consumption of wastewater reuse as rationale for prioritizing this option over desalination. However, the authors did not consider the additional trunk line construction cost for non-potable or indirect potable reuse of reclaimed water.

While the literature on the energy consumption of different options exists, most of these studies focus on characterizing and comparing the energy consumption of the fundamental physical processes in isolation. Little consideration is given to impacts arising from the manner in which these options impact the energy intensity of the water supply system (conveyance, etc…) that they are implemented into and the associated emissions impacts. These systematic effects are equally as important as the fundamental processes in influencing the holistic energy and emissions impact of securing the water supply with different options.

Additionally, the emissions impacts of deploying different options have typically been calculated using static factors for linking energy consumption with emissions, and have not captured the sensitivity of electric grid operation and evolution. This is especially important in the context of hydropower contribution uncertainty under climate change.

Finally, studies which examine renewable energy integration with water supply options also assume that renewable resources can be solely dedicated to these loads. This is not the case in practice, as renewable energy resources installed on the grid will serve the bulk grid load, therefore the emissions intensity of water supply options must take this into account. Few studies have compared different options on a basis that takes these sensitivities into account.

Capturing the scale of the options required to stabilize surface water reservoir levels was the focus of the first part of the study. This analysis represents the second of two parts, and is aimed at the following for this system:

- Comparing the *holistic* energy and emissions impacts of option portfolios that successfully stabilized major surface water reservoir levels, under historical (baseline) and climate-change augment conditions, taking into account operational effects on the water supply system, accurate scale, and electric grid evolution.
- The implications of securing the surface water reservoir levels for the ability of the system to meet renewable energy utilization goals.

With this comparison, quantitative insight into the factors that must be taken into account when choosing between different water supply options in the holistic context can be obtained.

2. Model description

The models used to carry out the energy impact analysis for stabilized reservoir levels from Part 1 are described here. The tools used in this part of the study consist of models for the energy consumption of individual water supply stabilizing options, capturing the effect of water supply infrastructure loads, and a detailed electric grid balancing model. Each of these tools is described as follows.

2.1. Water supply infrastructure energy impacts

Supplying water to end users for various uses in different regions across the state involves a number of processes to transport water to demand regions and treat it for use and environmental discharge. All of these processes use energy, and for components such as conveyance, have different energy impacts depending on their spatial distribution. In order to more accurately quantify the energy impact of implementing options to stabilize reservoir levels, the effect of these options on the energy usage of water supply infrastructure components must be captured. To accomplish this, the energy intensity of the operation of these infrastructure components must be factored into the model.

2.1.1. Conveyance

The primary water supplies for the state of California are equally distributed on a spatial basis across the state. A majority of the primary water supplies are sourced from precipitation/snowpack and river inflows in the northern and eastern regions of the state. A large portion of the water demand, especially for urban uses, is not located in proximity to these regions. The urban water demand is heavily biased towards the coastal regions where major cities are located. Therefore, energy must be used to transport water from these supply sources to demand regions.

Conveyance to most areas in northern California from supply regions requires very little energy, since it is based on gravity-driven flow through natural rivers. Only a small amount of pumping energy is required for transporting water across flat valley floors in certain regions. Conveyance to southern California, however, requires a relatively large amount of energy. The urban water demand is heavily focused in the South Coast and Colorado River regions, with the former containing 49% of the state's population (Anon., 2009a). Transporting water into this region requires pumping of water over long distances and over the Tehachapi Mountain Range, which poses a significant elevation barrier.

This study uses average factors for conveyance to meet the demand in each hydrologic region as outlined by the California Energy Commission (CEC) (Anon., 2005) as presented in Table 1. These factors represent the pumping energy usage of major conveyance projects such as the State Water Project. As a reference, the locations of these regions are presented in Fig. 1.

Table 1
Conveyance energy intensity for different hydrologic regions used in this study.

Group	Hydrologic regions included	Energy intensity
Northern California	North Coast Sacramento River North Lahontan San Francisco Bay San Joaquin River Central Coast Tulare Lake South Lahontan	150 kWh/MG
Southern California	South Coast Colorado River	8900 kWh/MG

2.1.2. Treatment

Depending on the intended end use, the extent of treatment required for water supplies may vary. Agricultural and industrial uses often do not require highly treated water, and the degree of chemical and biological contamination in source water depends on the specific region it is sourced from. Water use for residential and commercial use, however, requires treatment to potable standards, including the removal of harmful microorganisms, chemical compounds, and particulate matter.

Historical methods of water treatment including the use of chemical and mechanical methods do not require a significant amount of energy, however, new methods for treatment such as the use of ultraviolet radiation require more energy. Depending on end use and source, the energy intensity of water treatment ranges from 0 to 1600 kWh/MG. This study uses an average factor obtained by the CEC (Anon., 2005) for the energy intensity of the average treatment process of 100 kWh/MG.

2.1.3. Distribution

Once water is conveyed to a major city or town, it must then be distributed to each individual end user. This involves the pumping of water through pipe networks in cities and buildings, which may require a relatively high amount of energy. This study uses a representative factor from the CEC study of 1200 kWh/MG (Anon., 2005).

Fig. 1. Hydrologic regions in California (Anon., 2013a).

2.1.4. Wastewater treatment

Water that is collected post end-use must be treated in order to be safely discharged into the local environment or ocean areas. The extent of treatment required depends on the quality of the waste stream, the standards for discharge into a given area, and the processes used to carry out this treatment (activated sludge process, etc…). Depending on these factors, the energy intensity of wastewater treatment ranges between 1100 and 4600 kWh/MG (Anon., 2005). This study uses the representative value for California of 2500 kWh/MG (Anon., 2005).

2.2. Electric energy consumption of water supply stabilizing options

Many of the available options for securing water availability consume electricity to carry out their respective processes. The energy intensity of these options is discussed here.

2.2.1. Urban water conservation (UC)

Urban water conservation does not involve any direct processes that use electricity. This option simply involves the reduction of the raw urban water demand due to the installation of low flow hardware and reduction of leaks. The primary effect of this option is to reduce the amount of water that must undergo the infrastructure processes outlined previously and associated energy consumption.

This particular option affects all components of the water supply infrastructure. Water that is conserved is water that does not need to be conveyed, treated, distributed, and subject to wastewater treatment. The temporal profile of the reduction in infrastructure loads is based on a study of the hourly behavior of urban water demand components by Funk (Funk, 2011) in California, taking into account indoor and outdoor usage profiles.

2.2.2. Water reuse (PR)

This study considers three processes for the reuse of wastewater treatment plant effluent: microfiltration (MF), reverse osmosis (RO), and ultraviolet/hydrogen peroxide (UV/H_2O_2) advanced oxidation process. These processes are used for treating wastewater to be reused via indirect potable reuse.

The energy footprint of these processes has been studied in depth by Sobhani (2011), for a water reuse plant with indirect potable application that is currently operating in Pacific Coast area. The energy intensities of these individual processes which are utilized in this study are presented in Table 2. The hourly profile of these loads is tied to the temporal profile in wastewater treatment plant influent flow. All three processes follow this same profile, which is also presented by Sobhani (2011).

Water reuse also affects the infrastructure loads primarily by displacing the conveyance component. Using recycled water to meet local demands reduces the amount of water that must be pumped into the region through the conveyance system, provided that coordination between local and central water management authorities takes place. Depending on region, however, additional pumping may be required to transport water from the reuse plant to local-use reservoirs. This option also does not displace any of the other infrastructure component loads. Treatment must still take place since this model assumes

Table 2
Energy intensity of water reuse processes.

Process	Average energy intensity [kWh/MG]
Microfiltration	845
Reverse osmosis	2025
UV/H_2O_2 AOP	302

indirect potable reuse; water supplied by this measure must still be distributed to end users and treated in wastewater treatment plants.

2.2.3. Thermal desalination (TD, TDw)

To capture the energy consumption of thermal desalination plants, a detailed, first-principles model of a multi-effect evaporation thermal desalination plant developed by Ettouney (2004) is used. This type of thermal desalination plant operates by evaporating intake water in a series of decreasing pressure vessels known as effects, by spraying feed seawater on a series of tubes that are heated by hot steam. The use of an MEE configuration was selected for its ability to use relatively low temperature heating steam to drive its processes.

The MEE-TVC process operates as follows. Intake saline water is fed into the cold side of a steam-to-liquid condenser, where it receives thermal energy from hot vapor from the last effect of the system. A portion of this seawater was used only for cooling purposes, and is discharged back into the sea. The remaining seawater is the stream that will be desalinated and is termed the feed seawater. The feed seawater is pumped into a series of nozzles placed at the top of pressure vessels called effects. In each effect, the nozzles spray the seawater onto a series of tubes containing hot steam and receive thermal energy through conduction and convection, causing it to separate into a two-phase mixture. The liquid phase, which contains all of the salt and other chemical constituents, falls to the bottom of the effect where it is collected and discharged as brine. The remaining content consists of vapor-phase water and non-condensable gasses that may have been dissolved in the intake seawater. This vapor mixture rises to the top of each effect, where the non-condensable gasses are removed and discharged into the atmosphere, and the vapor-phase water is fed into the tubes of the next effect to be used as the hot-side heat transfer fluid for another spray of seawater. Once the fluid in the tubes is cooled, it is condensed and collected as distillate. The process continues sequentially for each effect in the system. Each subsequent effect is maintained at lower pressures than the previous effect. This is necessary to encourage evaporation while the temperature of the hot-side heat transfer fluid in each subsequent effect is decreasing in temperature. This vacuum is maintained by vacuum pumps operating on the last effect of the system.

Once the last effect is reached, the vapor mixture is fed as the hot-side heat transfer fluid for the condenser. After being slightly cooled, a portion of this vapor condenses and is collected with the distillate. The remaining vapor, termed the entrained vapor, is fed for use in a thermocompressor (ejector) to supplement the mass flow of the motive steam. The motive steam is the high-pressure, high temperature working fluid that provides the thermal energy for the system, and is sourced from an external reservoir. The entrained vapor is compressed and added to the motive steam flow. This combined stream is called the heating steam flow, and is introduced into the tubes of the first effect as the hot-side heat transfer fluid. Note that once this fluid condenses, it is not collected as distillate, but rather fed back to the external reservoir to be heated and pressurized before being recycled back into the system.

The use of the thermocompressor is advantageous over the standard Multiple-Effect Evaporation system since recycling of the vapor allows recovery of latent heat, reducing motive steam and thermal energy requirements.

A diagram of an MEE-TVC plant is presented in Fig. 2.

The utilized model is a first principles-based heat transfer and thermodynamic model. The model by Ettouney utilizes a Newton–Rhapson iteration method to sequentially solve the mass balance, species, and energy balance equations in each effect. The mass balance is determined by the split of the feed stream flow into brine and distillate flows. For the first effect:

$$\dot{m}_{\text{feed},1} = \dot{m}_{\text{brine},1} + \dot{m}_{\text{distillate},1}$$

For subsequent effects:

$$\dot{m}_{\text{feed},i} = \dot{m}_{\text{brine},i} - \dot{m}_{\text{brine},i-1} + \dot{m}_{\text{distillate},i}$$

The salt balance is determined in the first effect by:

$$X_{\text{feed},1} \cdot \dot{m}_{\text{feed},1} = X_{\text{brine},1} \cdot \dot{m}_{\text{brine},1}$$

where the salinity of the vapor distillate is assumed to be small, such that the term corresponding to the salt concentration in the distillate is negligible. For subsequent effects, this is determined by:

$$X_{\text{feed},1} \cdot \dot{m}_{\text{feed},1} = X_{\text{brine},1} \cdot \dot{m}_{\text{feed},1} - X_{\text{brine},i-1} \cdot \dot{m}_{\text{feed},i-1}$$

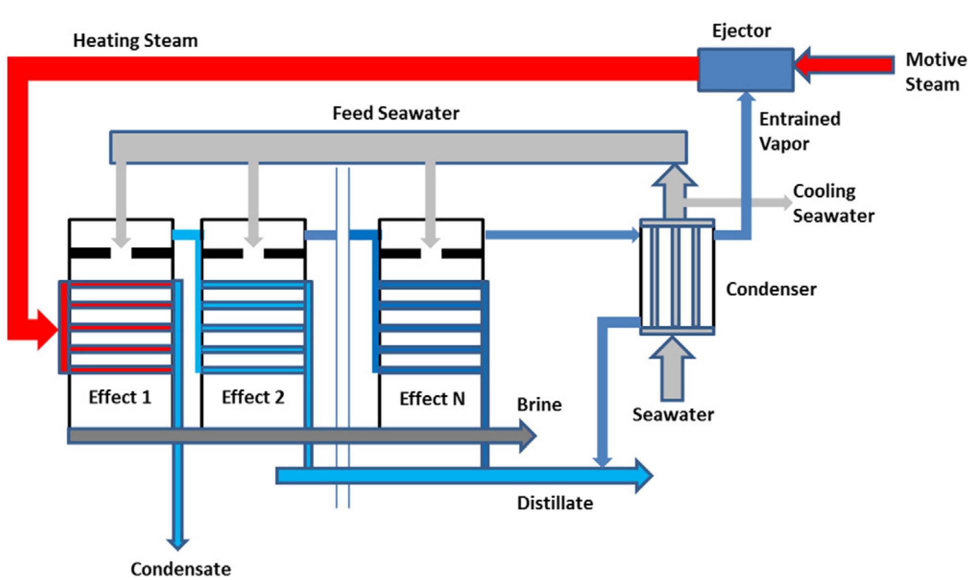

Fig. 2. Diagram of an MEE–TVC desalination plant.

The energy balance resolves the balance between the latent heat of the condensing heating steam, the latent heat of the vapor distillate, and the sensible heat of the feed seawater in the first and second effects:

$$\dot{m}_{\text{stean}} \cdot L_{\text{steam}} = \dot{m}_{\text{feed},1} \cdot C_p \cdot (T_{b1} - T_{\text{feed}}) + \dot{m}_{\text{distillate},1} \cdot L_{\text{distillate},1}$$
$$\dot{m}_{\text{distillate},1} \cdot L_{\text{steam}} + \dot{m}_{\text{bf},1} \cdot L_{\text{bf},1} = \dot{m}_{\text{feed},2} \cdot C_p (T_{b2} - T_{\text{feed}}) + \dot{m}_{\text{distillate},2} \cdot L_{\text{distillate},2}$$

where L is the latent heat of vaporization of the given flow stream, and 'bf' refers to the vapor flashed off from the brine. For subsequent effects, input energy is sourced from vapor formed in the previous effect ('distillate $i - 1$') and the flashing of the product condensate ('df') and brine ('bf'). This provides the following energy equation for subsequent effects 'i':

$$\dot{m}_{\text{distillate},i-1} \cdot L_{\text{distillate},i-1} + \dot{m}_{\text{bf},i-1} \cdot L_{\text{bf},i-1} + \dot{m}_{\text{df},i-1} \cdot L_{\text{df},i-1} = \dot{m}_{\text{feed},1} \cdot C_p \cdot (T_{bi} - T_{\text{feed}}) + \dot{m}_{\text{distillate}} \cdot L_{\text{distillate},i1}$$

Taking into account allowances for boiling point elevation and non-equilibrium allowance, the mass flows, concentrations, and temperatures of the relevant flow streams in each effect are resolved. More details can be found by Ettouney (2004).

Primary inputs for the plant design involve the plant capacity, number of effects, heating steam and reject brine temperature and salinity (of each effect), and dimensions and heat transfer parameters for plant components. Inputs for inlet water conditions include intake seawater temperature, and salinity. For this study, the major input parameter settings used are presented in Table 3. The number of effects and heating steam temperature was chosen to maximize the performance ratio of the plant within practical limits of pressure management and preventing scaling in plant components.

Using this model, the electric energy and thermal energy consumption can be calculated. The electric energy consumption of thermal desalination plants is primarily based on internal plant pumping loads, which are an output of the model. The thermal energy consumption is calculated from the difference in enthalpies of the heating steam entering the first effect and that of the condensate reject from this first effect, both of which can be calculated from temperatures and pressures in the model as follows:

$$\dot{Q} = \dot{m}_{\text{HS}} * \left(h_{\text{HS}}(T,P) - h_{\text{CR},E1}(T,P)\right)$$

Using these parameters, the specific electric and thermal energy consumption of this plant type are calculated and presented in Table 4.

The thermal energy supply is provided either by waste heat or by natural gas. Due to limits on the waste heat potential as calculated from eGRID data for coastal power plants (Anon., 2013b), the capacity of the former is limited. The hourly profile of this load is assumed to be steady.

Table 3
Input parameter values for MEE plant model.

Input parameter	Value
Number of effects	12
Single plant capacity	40,000 m^3/d
Heating steam temperature	60 °C
Intake seawater temperature	25 °C
Intake seawater salinity	36,000 ppm

Table 4
Specific electric and thermal energy consumption of the representative MEE plant.

Energy type	Specific consumption rate [kWh/m^3]
Electric	2.67
Thermal	67.14

2.2.4. Membrane desalination (MD)

The energy consumption of membrane desalination plants was also calculated by use of a first-principles model of a reverse osmosis plant developed by Ettouney (Anon., 2013b). For this study, a two stage seawater reverse osmosis desalination plant configuration is used due to its relatively low energy consumption per unit of freshwater produced. Plant design parameters include plant capacity, permeate pressure, feed temperature, and flow/salinity parameters for each element. The major input parameters used as inputs to the model are shown in Table 5.

All other parameters are set to the model default value for seawater desalination. Using this model, the specific electric energy consumption of a plant with this design is calculated as an output of the model to be about 4.7 kWh/m^3 of water produced.

2.3. Electric grid model and greenhouse gas emissions

Once calculated, the electric loads of the water supply stabilizing measures are added (or subtracted, if applicable) to the bulk load of the electric grid. To determine the energy use and emissions impact of these loads and their interaction with renewable resources, an electric grid model which captures the behavior of conventional and renewable resources to meet this load is utilized and described here.

This study utilizes the Holistic Grid Resource Integration and Deployment (HiGRID) model developed by Eichman (Eichman et al., 2013; Eichman, 2012) to capture the emissions impacts and grid performance of the aggregate electric load demand, which is a major part of the larger Spatially and Temporally Resolved Energy and Environment Tool (STREET) platform. The HiGRID model is a large scale, integrated model which can capture the details of technical and economic effects of implementing a wide variety of resources. Not all of these options are relevant to this study, however. Therefore, a simplified schematic of the model incorporating the options and outputs relevant to this study is presented schematically in Fig. 3. More details about the model's other capabilities are presented by Eichman (2012) and Tarroja et al. (2014).

The modules are described as follows:

Renewable Generation Module This module takes the capacity of different renewable resources as an input, and uses models of each type to determine the time-resolved profile of power generation and power delivered to load for each resource type. The resource types included are Solar PV (fixed, 1-axis tracking, 2-axis tracking, concentrated), Wind, Geothermal (binary and flash), Biomass/Biogas, and Small Hydropower. More details on these modules are presented by Eichman (2012).The costs associated with utilization of these resource types are also calculated and factored into the cost of generation module. The generation profile of the combined renewable resource mix is composed and fed into the dispatchable load module.

Table 5
Input parameter values for SWRO plant model.

Input parameter	Value
Single plant capacity	40,000 m^3/d
Permeate pressure	101 kPa
Feed temperature	25 °C
Intake seawater salinity	36,000 ppm

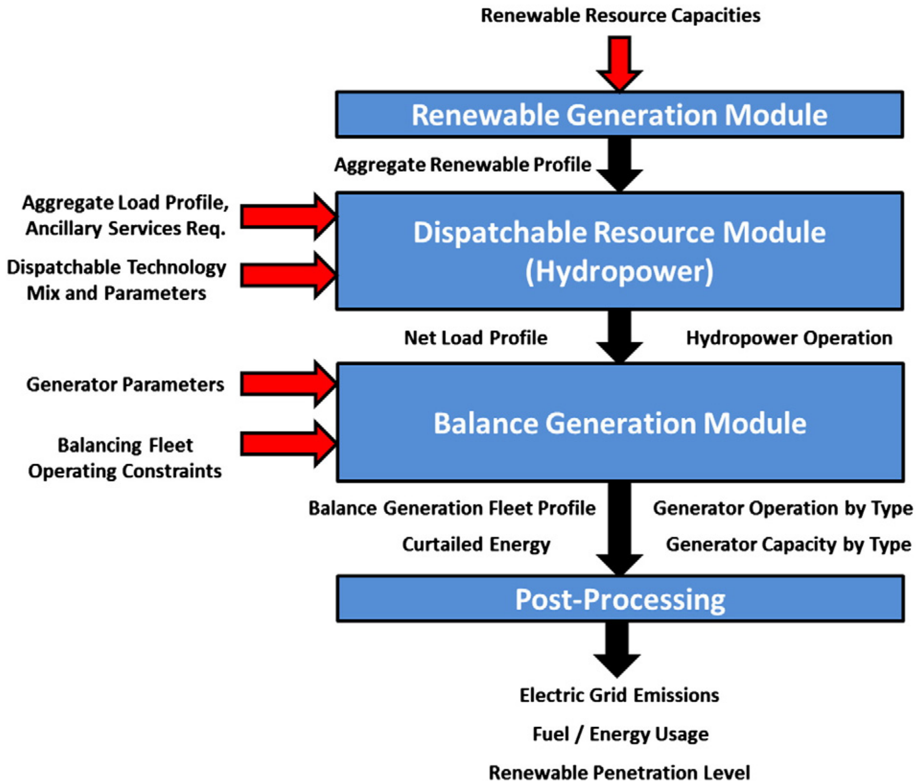

Fig. 3. Simplified HiGRID model schematic, showing components relevant to this analysis.

Dispatchable Resource Module The dispatchable load module takes the time resolved electric demand profile and aggregate renewable generation profile as inputs to compose the net load profile. This module dispatches the behavior of non-fossil power plant resources loads in response to the behavior of the net load profile or the behavior of balance generators through an iterative process, within the operating constraints of each technology. For this study, the only option used is large hydropower. The temporally resolved behavior of large hydropower resources is captured using the model developed by Chang et al. (2013), which simulates the behavior of conventional (large) hydropower, run-of-the-river hydropower, and pumped hydropower resources based on available inflow, aggregate reservoir fill conditions, and electric grid reliability constraints. After this resource is dispatched, the adjusted net load profile and the remaining portion of ancillary services which balancing generators must meet are produced and fed into the balance generation module. More details can be found in Eichman (2012).

Balance Generation Module The balance generation module determines the sizing and dispatch of base-load, load-following, and peaking generation that is required to meet the adjusted net load profile and remaining ancillary services, within the performance capabilities of different generator classes. Base-load generators such as nuclear and coal power plants are dispatched on an installed capacity and monthly capacity factor basis that includes planned outages, and have flat operating profiles within each month. Load-following and peaking generators are dispatched to meet the remainder of the adjusted net load profile. Each of these classes of generators has performance limitations including minimum operation time, ramping limitations, part-load operation range, and generator size. Additionally, the maximum and minimum numbers of load-followers and peaking generators are also considered. The algorithm for dispatching these generators and a further description of their parameters are presented in detail by Eichman (2012). The operation of balance generators determined in this module can also be re-fed back into the dispatchable load module to allow technologies to respond specifically to certain aspects of the balance generator fleet (i.e. number of peaking generators) in an iterative process.

Post-Processing The results from all of the previous modules are used to calculate electric grid emissions, energy usage, and the fraction of the load demand served by renewable resources by knowledge of the operating characteristics and capacity of each grid resource. As part of the post-processing, the greenhouse gas emissions are calculated from the fuel consumption of each of the different types of technologies operating on the electric grid, which is determined from their hourly operation. For load-following and peaking power plant technologies, fuel consumption varies as a function of efficiency, which varies every hour due to changes in the part-load operating condition required to follow the electric load demand. Additionally, for water supply resources such as thermal desalination, fuel is directly consumed for the desalination process. For different fuel types, the emissions factors used in this model are shown in Table 6.

It is important to note that these emissions factors account for the in-operation emissions of the corresponding grid resources. These factors do not include upstream greenhouse gas emissions (such as mining or fuel transport). The renewable resources considered in this study do not produce greenhouse gas emissions in operation.

Table 6
Emissions factors for different fuel types (Anon., 2013c).

Fuel type	Emissions factor [Tonnes CO_2/Million British Thermal Units (MMBTU) fuel consumed]
Natural gas—U.S. weighted average	0.05302
Aggregated coal—electric utility mix	0.09438
Nuclear	0.0000

Table 7
Successful water stabilization portfolios—baseline conditions, capacities in Mm^3/d.

Designation	UC	TDw	TD	MD	PR
TD	0.00	0.00	7.60	0.00	0.00
MD	0.00	0.00	0.00	7.60	0.00
MD (SC)	0.00	0.00	0.00	7.10	0.00
PR	0.00	0.00	0.00	0.00	7.00 (38%)
UC/PR (GH)	6.83 (100%)	0.00	0.00	0.00	0.55 (3%)
MD/UC	6.83 (100%)	0.00	0.00	0.65	0.00

3. Metrics and approach

3.1. Water scenarios for analysis and renewable energy rollout

This study takes the water supply stabilization option portfolios which were able to successfully stabilize reservoir levels as determined in Part 1, and determines their energy and emission impacts as well as their implications for renewable energy utilization. This is conducted for each successful portfolio and renewable capacity combination. For reference, these cases are presented in Table 7 for baseline conditions (BAS) and in Table 8 for climate change augment conditions (CCHa).

The GH case represents the portfolio which was configured for minimum greenhouse gas emissions, as determined by the impacts identified in the Results section.

For each successful portfolio, the time-resolved electric load profile is calculated and added to the bulk electric load demand profile for California, as obtained from CAISO data for the year 2005 (California Independent System Operator, 2012). This is conducted for increasing amounts of renewable generation, based on projections by the California Public Utilities Commission (CPUC) up to a 33% base renewable penetration level (Anon., 2009b), but adjusted for grid constraints and curtailment. The base renewable penetration level represents the fraction of the electric load demand that is served by renewable resources without load from transportation or water supply sectors in excess of historical trends. Beyond the 33% base renewable penetration level, the rollout is based on capacity limits and capacity factors of available renewable resources. The renewable mix used in this study is presented in Fig. 4.

Without any additional load, the base renewable penetration level under baseline conditions spans from 10.7% to about 64.8%. The capacity of installed regional wind resources flattens out after a given base renewable penetration level due to wind resource potential limits in California. Above this capacity, wind turbines would have to be installed in areas with low wind speeds and may not be economically feasible.

3.2. Grid input modifications for climate change conditions

For the climate change augment conditions, which represents the 2040–2050 time period, the population of the state is expected to increase from about 35.2 million (2005) to 49.1 million (2045). Therefore, the raw electric load demand scales with population accordingly for these conditions, being increased by a factor of 1.39. The temporal profile of the raw load demand, however, remains the same. Due to this load increase, the base renewable penetration under these conditions is lower for a given installed renewable capacity amount.

Table 8
Successful water stabilization portfolios—climate change augment conditions, capacities in Mm^3/d.

Designation	UC	TDw	TD	MD	PR
TD	0.00	0.00	34.00	0.00	0.00
MD	0.00	0.00	0.00	34.00	0.00
MD (SC)	0.00	0.00	0.00	30.50	0.00
MD/UC	9.50 (100%)	0.00	0.00	19.50	0.00
MD/PR	0.00	0.00	0.00	7.20	18.44 (100%)
P1	9.50 (100%)	0.00	0.00	7.40	18.44 (100%)
P2 (GH)	9.50 (100%)	3.63 (100%)	0.00	5.00	18.44 (100%)

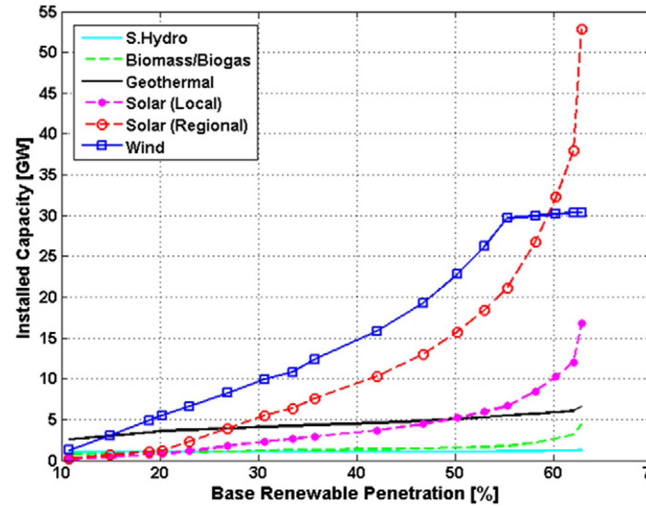

Fig. 4. Renewable mix vs. base renewable penetration level under baseline conditions.

Under the climate change augment conditions, the reservoir inflows are affected, which also affects the water available for hydropower generation. The hydropower module used in the HiGRID model takes in a bulk stream flow vector, the details of which are presented in (Chang et al., 2013). To handle this effect in our study, at each time step, the difference between the aggregate reservoir inflows between baseline and climate change augment conditions was calculated and normalized by the baseline condition value. This scaling profile is then applied to the bulk stream flow vector used for the baseline conditions to create a bulk stream flow vector for climate change augment conditions. This is then used as the input to the HiGRID hydropower module.

3.3. Metrics

For each successful water option portfolio and renewable capacity combination, the following metrics are calculated to evaluate the energy and emissions effects of implementing these options.

Greenhouse gas (GHG) emissions: This refers to the total greenhouse gas emissions emitted annually by the combined water supply and electricity sectors. This includes all direct emissions from water stabilization options, and all emissions due to generation resources on the electric grid. The electric loads associated with water stabilization options do not cause direct emissions, rather, these are accounted for by increasing the electric load on the grid and therefore a change in electric grid greenhouse gas emissions. This accounts for CO_2, N_2O, and CH_4 emissions, and is presented in million metric tons of CO_2 equivalent (CO_2e).

Incremental GHG intensity: This refers to the incremental increase in greenhouse gas emissions to provide one cubic meter of water (or displace an equivalent demand) from the different individual options, taking into account direct and systematic energy impacts.

Renewable Penetration Level: This refers to the fraction of the total electric load demand (including that due to water supply stabilization options) that is served by renewable resources. This is important for measuring the progress towards meeting the Renewable Portfolio Standard goals of the state or a given region.

4. Results

4.1. Effects of climate change on grid performance

Before a discussion of the greenhouse gas effects of implementing the option portfolios that successfully stabilized surface water reservoir

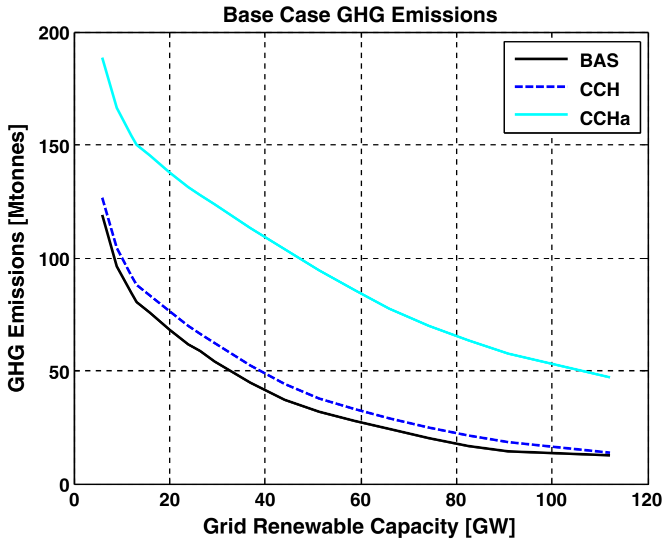

Fig. 5. No-option combined water–electricity greenhouse gas emissions.

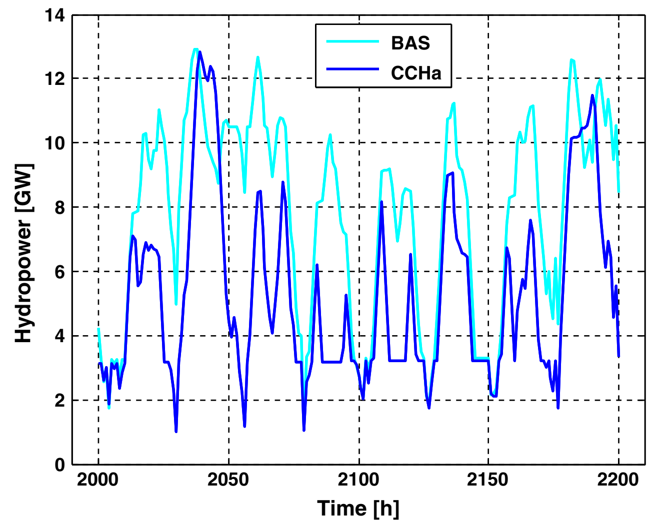

Fig. 7. One-week hydropower profiles for BAS and CCHa cases—82.5 GW RE.

levels identified in Part 1, it is important to discuss the differences between the no-option cases for the baseline and climate change augment conditions. The greenhouse gas emissions as a function of installed renewable capacity for the no-option cases and both hydrology conditions are displayed in Fig. 5.

Three cases are displayed. The BAS case refers to baseline conditions, the CCH case refers to climate change augmented inflow conditions but no electric load demand growth, whereas CCHa includes both augmented inflow and demand growth. As expected, emissions decrease with increasing installed renewable capacities for all cases.

The CCH case shows only slight increases in GHG emissions compared to the BAS case. This increase is primarily due to the reduction in hydropower generation, brought about by reduced reservoir inflow. The deficit in generation must be compensated for by other resources on the grid, primarily natural-gas fired load-following power plants, increasing fuel consumption and therefore emissions. However, while the reduction in inflow due to climate change in this region may be large—on the order of 30-35%, hydropower only comprises a fraction of the grid energy mix. The increase is between 7.83 Mtons of CO_2e at low renewable capacities and 4.21 Mtons of CO_2e at high renewable capacities. While this can be up to 7% of the combined system greenhouse gas emissions, it is small compared to the effect of electric load demand growth due to population. This is evidenced by the difference between the CCHa and CCH cases.

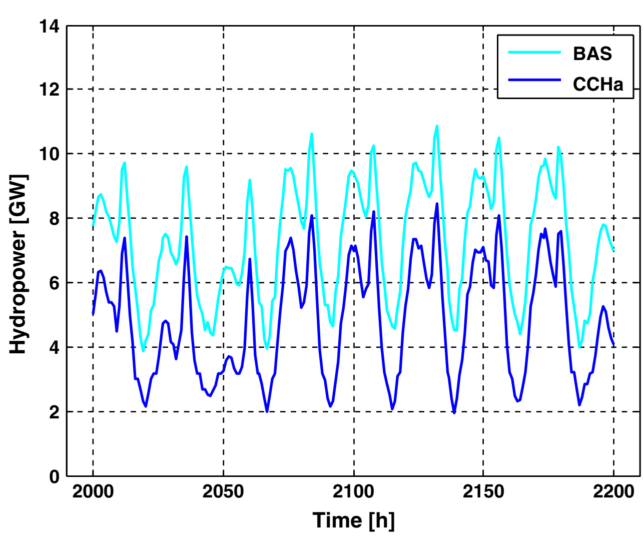

Fig. 6. One-week hydropower profiles for BAS and CCHa cases—5.9 GW RE.

An additional aspect to consider is the effect that climate change inflows will have on the dispatch of hydropower. Hydropower serves an important role on the electric grid by providing load following generation to balance the electric load demand and ancillary services capacity to maintain grid reliability. With increased renewable capacity, these functions are more valuable due to wind and solar power intermittency. Therefore, the reduction of reservoir inflow does not only affect greenhouse gas emissions, but also the dispatch of hydropower resources. Sample profiles for the dispatch of hydropower generation at low and high installed renewable capacities are presented in Figs. 6 and 7, respectively.

With low renewable capacities installed, the behavior of hydropower generation under climate change augment conditions is the same as that under baseline conditions, but scaled down. This is because the variability that hydropower must balance is small. At high renewable capacities, however, the manner in which hydropower plants are dispatched under reduced inflow is no longer a scaled down version of that under baseline inflow. In order to provide ancillary services to maintain grid reliability while balancing renewable intermittency with reduced inflow, these power plants must be dispatched differently. A full analysis of these effects is beyond the scope of this work, however, this behavior implies that the management of hydropower plants and their role on the electric grid may need to be altered under climate change augment conditions. This is a subject of future work.

4.2. Incremental GHG emissions of water supply stabilizing options

To understand the results for the effect of implementing the water supply option portfolios that successfully stabilized reservoir levels on greenhouse gasses, it is important to understand the impacts of the individual options that compose those portfolios. This includes not only their direct effects on emissions through their specific processes, but also their effect on the electric loads associated with conveyance, treatment, distribution, and wastewater treatment.

A breakdown of the components of the greenhouse gas impacts for implementing each of the individual options evaluated in this study is displayed in Fig. 8, for a 10.7% grid renewable penetration level. It is important to note that since many of the emissions due to these options are through their effects on the electric grid, the renewable penetration level of the electric grid influences these results. The southern California-biased membrane desalination option is also

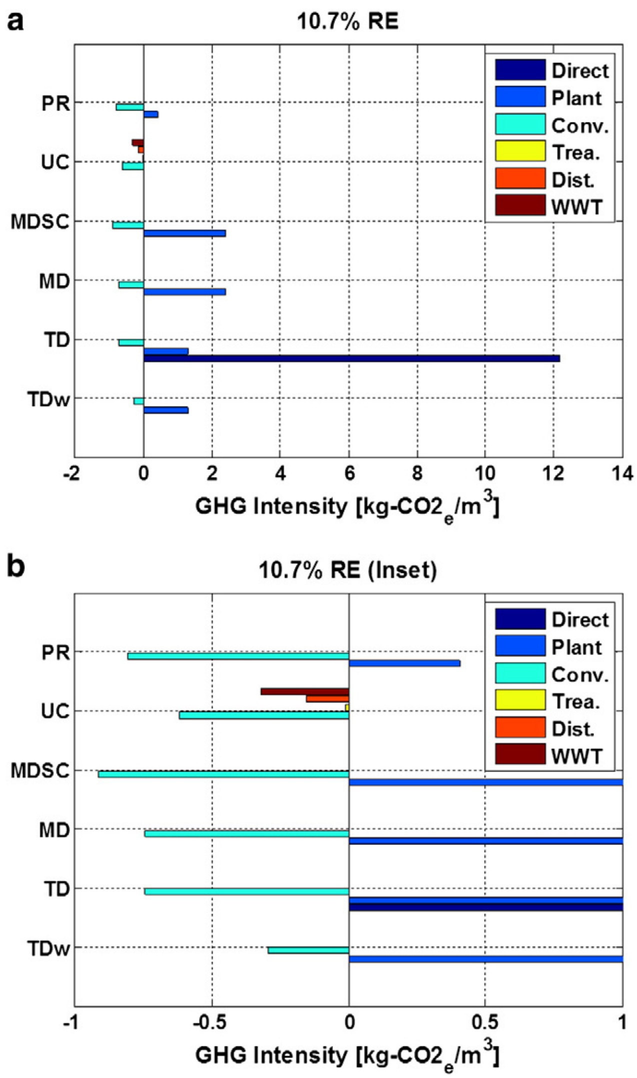

Fig. 8. Greenhouse gas intensity breakdown for different individual options at a 10.7% grid renewable penetration level (a), inset (b).

added for comparison. Each option affects total system greenhouse gas emissions through their effect on different components. These are described as follows:

Direct: Greenhouse gas emissions that are directly emitted from the option processes
Plant: Emissions due to the additional electric loads placed on the grid from the option processes
Conveyance: Effect on emissions due to the displacement of water conveyance loads (i.e. pumping)
Treatment: Effect on emissions due to the displacement of water pretreatment loads
Distribution: Effect on emissions due to the displacement of loads associated with distributing water to end users
Wastewater treatment (WWT): Effect on emissions due to changes in wastewater treatment plant loads

Some of the greenhouse gas emissions intensity components for a given measure can be negative. This indicates that greenhouse gas emissions are reduced due to the effects of individual options on these components. For example, an acre-feet of water conserved in a certain region is one which does not have to be pumped or conveyed to that region, reducing the associated electric load and therefore greenhouse gas emissions. These effects will be described in detail for each option.

Water reuse (PR) produces greenhouse gas emissions due to the electric loads associated with the processes: microfiltration, advanced oxidation processes, and reverse osmosis. Per cubic meter of water produced from this option, these plant loads contribute about 0.406 kg CO_2e at this renewable penetration level. For the California system, however, the majority of wastewater treatment plant capacity is located in the southern region. Conveying water to this region is very energy intensive. By meeting local demand with water reuse, less water must be pumped into the region, reducing electric loads and greenhouse gas emissions by about 0.808 kg CO_2e. Therefore, the net effect of implementing this option on greenhouse gas emissions is actually negative. This measure does not affect other components, however, since it does not modify the raw water demand.

Urban water conservation (UC) has significant benefits for emissions due to the effects it has on the water supply infrastructure electric loads. Conserving water has no direct or process emissions. Furthermore, a given amount of water conserved in a given region is one which does not have to be conveyed into the region, treated, distributed to end users, and flowed through wastewater treatment plants. Therefore, this option displaces electric loads from all of these processes, contributing to a net negative effect on greenhouse gas emissions. The benefit of displacing conveyance loads for this option is not as large as that for water reuse due to differences in the spatial distribution of where it is implemented.

Membrane desalination (MD) also produces greenhouse gas emissions due to electric loads associated with the seawater reverse osmosis process, which is relatively energy intensive compared to the other options. This component contributes 2.42 kg CO_2e per cubic meter at this renewable penetration level, but displaces conveyance loads due to a large concentration of coastal population in southern California, reducing emissions by 0.743 kg CO_2e per cubic meter. The net effect is still positive, however. When membrane desalination capacity is more biased towards the southern California region (MDSC), the emissions reduction due to conveyance is increased to 0.914 kg CO_2e per cubic meter, but the net effect is still positive.

Thermal desalination with direct natural gas (TD) produces the largest emissions contributions. To provide heat for the multi-effect evaporation (MEE) process, a relatively large amount of natural gas must be burned, resulting in large direct emissions of about 12.2 kg CO_2e per cubic meter. Electric loads due to pumping loads in the plants themselves also contribute 1.29 kg CO_2e per cubic meter, while displacement of conveyance loads is the same as that for membrane desalination since it is based on urban coastal population distribution.

Thermal desalination with waste heat (TDw) has the same plant-based emissions as that with natural gas, but has no direct emissions since no additional fuel is being burned. This option has a reduced beneficial effect on displacing conveyance loads, however, since a large fraction of the waste heat potential is in the central and northern California regions, where the conveyance load is small.

The relative ordering of the individual options remains the same as the renewable penetration level of the electric grid is increased. All of the component effects of each option, except that of direct emissions, scale with grid renewable penetration since they are based on electric loads. The breakdown of the components of the greenhouse gas impacts for implementing each of the individual options at a 20.1% and 50.3% grid renewable penetration level is presented in Figs. 9 and 10, respectively. The inset figures are shown, since the scale of the direct emissions due to thermal desalination with natural gas does not change with renewable penetration.

As the renewable penetration is increased, the incremental emissions for all components based on electric loads decrease in magnitude. The net incremental effect of implementing the individual options at different renewable penetration levels is summarized in Table 9.

These results emphasize the importance of considering systematic effects when evaluating the greenhouse gas impacts of water supply stabilization options. The net effect of these options is the metric that

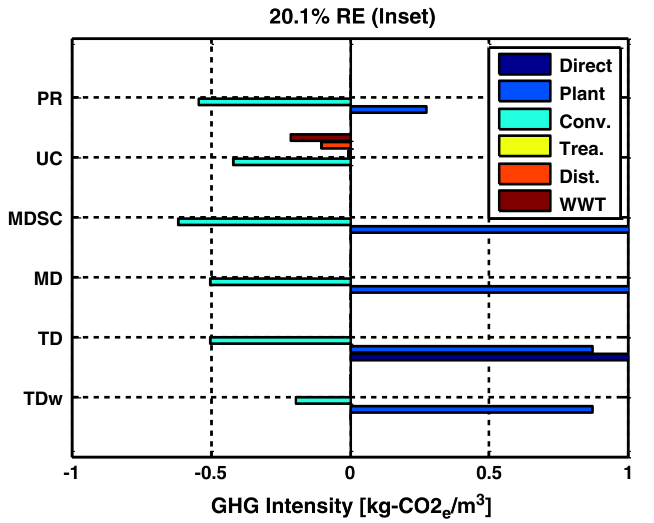

Fig. 9. Greenhouse gas intensity breakdown for different individual options at a 20.1% grid renewable penetration level.

is important to consider, and should be used as a criterion for deciding how much of each options to use to stabilize reservoir levels on a greenhouse gas emissions basis. For these systematic effects to be realized in the real system, however, coordinated water supply management must be implemented. Regions implementing these options must communicate with the entities that manage the water supply system, such that energy is not wasted by conveying water to a region where it will not be needed.

From a policy standpoint, these results have implications for determining a priority for water supply stabilization measures while taking into account energy impacts. When setting this priority, the impacts on system energy consumption as well as the direct energy consumption of a given option are important to consider. Conservation-based options should be given the highest priority and near-term incentives due to its co-benefits for water supply stabilization and greenhouse gas emissions reduction. Water reuse takes the next priority, since its deployment still has co-benefits in this sense. Thermal desalination with waste heat, while energy intensive, has the third priority since these units utilize already existing energy resources and minimize the

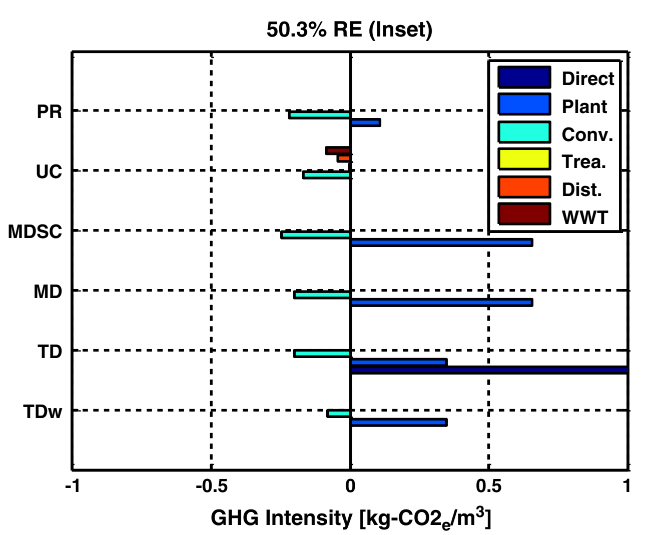

Fig. 10. Greenhouse gas intensity breakdown for different individual options at a 50.3% grid renewable penetration level.

Table 9
Net incremental GHG intensity [kg-CO_2e/m^3].

Option	10.7% RE	20.7% RE	50.3% RE
TDw	1.0017	0.6782	0.2710
TD	0.5494	0.3719	0.1486
MD	1.6767	1.1352	0.4536
MD (SC)	1.5055	1.0192	0.4073
UC	−1.1071	−0.7495	−0.2995
PR	−0.4018	−0.2720	−0.1087

greenhouse gas impact of water production. Finally, membrane desalination, which has the highest specific greenhouse gas emissions at present, takes the last priority as it is used to compensate for the limited capacity of the other measures.

As the grid becomes more renewable, however, the energy impacts of water supply stabilization measures are decreased. The greenhouse gas reduction of measures such as conservation and reuse is still present but to a lesser extent. Similarly, the greenhouse gas penalty of desalination is reduced at higher renewable penetration levels. This indicates that the rollout of water supply stabilization measures should be coordinated in time with the renewable evolution of the electric grid. In the near term, while the grid is carbon-intensive, the focus should be on deploying co-beneficial options to capacity. In the long-term, when the co-beneficial options are exhausted, the grid will hopefully have evolved to enough of a renewable mix to minimize the greenhouse gas penalty of options such as desalination.

4.3. Greenhouse gas impacts of securing water availability

With an understanding of the net effect of individual options on greenhouse gas emissions, the greenhouse gas impacts of the individual and hybrid option cases that successfully stabilized surface reservoir levels determined from Part 1 can be discussed. The change in the greenhouse gas emissions from the no-option case as a percentage of the no-option case emissions for each of the successful portfolios is presented in Fig. 11 for baseline conditions and in Fig. 12 for climate change augment conditions.

Under baseline conditions, three of the successful water stabilization option portfolios (PR, MDUC, GH) have a near-neutral or beneficial impact on the greenhouse gas emissions of the system. Since many of these emissions are through the interaction with the electric grid, the benefits increase with increased renewable capacities on the grid. The exception occurs at very high renewable capacities, where mismatch between renewable generation and water stabilization option loads causes these loads to be met with natural gas instead of renewables. This reduces the benefit of these three cases compared to the base case, but increases the benefit of the MD case, since the latter is able to utilize otherwise-curtailed renewable generation.

The use of thermal desalination with natural gas, as expected, significantly increases GHG emissions compared to the base case. The high direct emissions of this option do not decrease with renewable capacity since they are not electric in nature.

The MD case shows increases in the change in GHG emissions as a percentage of the base case with renewable capacity, due to the additional load placed on the grid that must be met with additional natural-gas power plant generation. Note that this does not indicate that membrane desalination is increasing the absolute GHG emissions as more renewable capacity is being added. Recall that the base case emissions decrease with renewable capacity installation. Therefore, this increase indicates that the emissions due to the membrane desalination load demand are not decreasing at the same rate as the rest of the bulk grid. This also is due to a lower coherence in the profiles of desalination loads and renewable generation, compared to that of the bulk grid load and renewable generation.

Under climate change augment conditions, all of the option portfolios that were successful at securing water availability cause an increase in

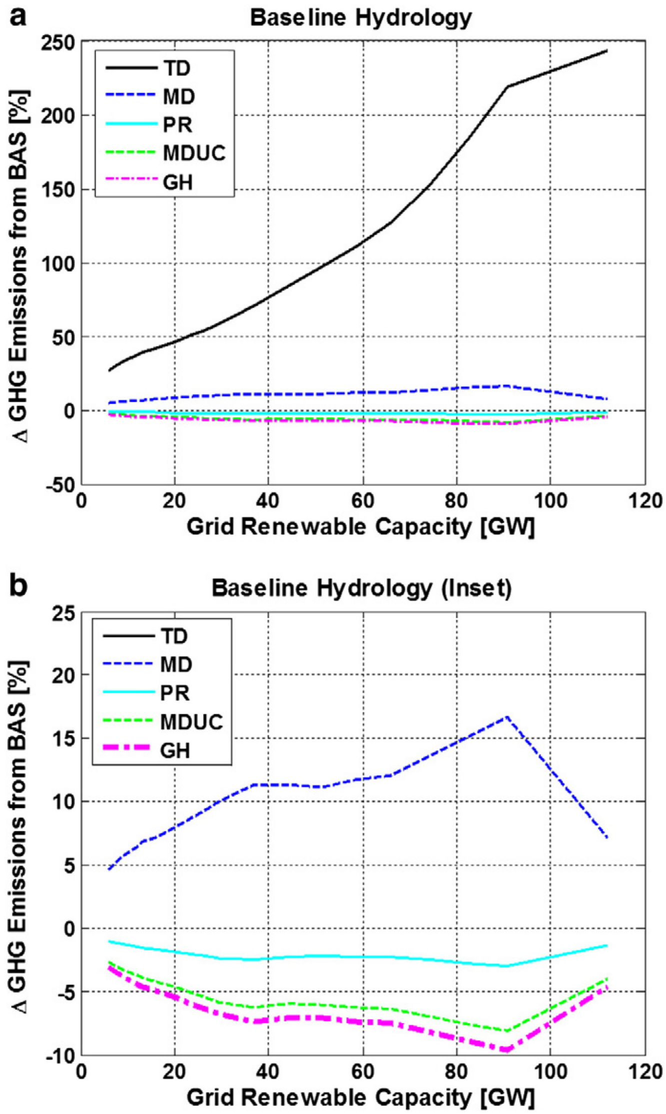

Fig. 11. Change in greenhouse gas emissions from the no-option case under baseline conditions as a percentage of the no-option case value vs. grid renewable capacity.

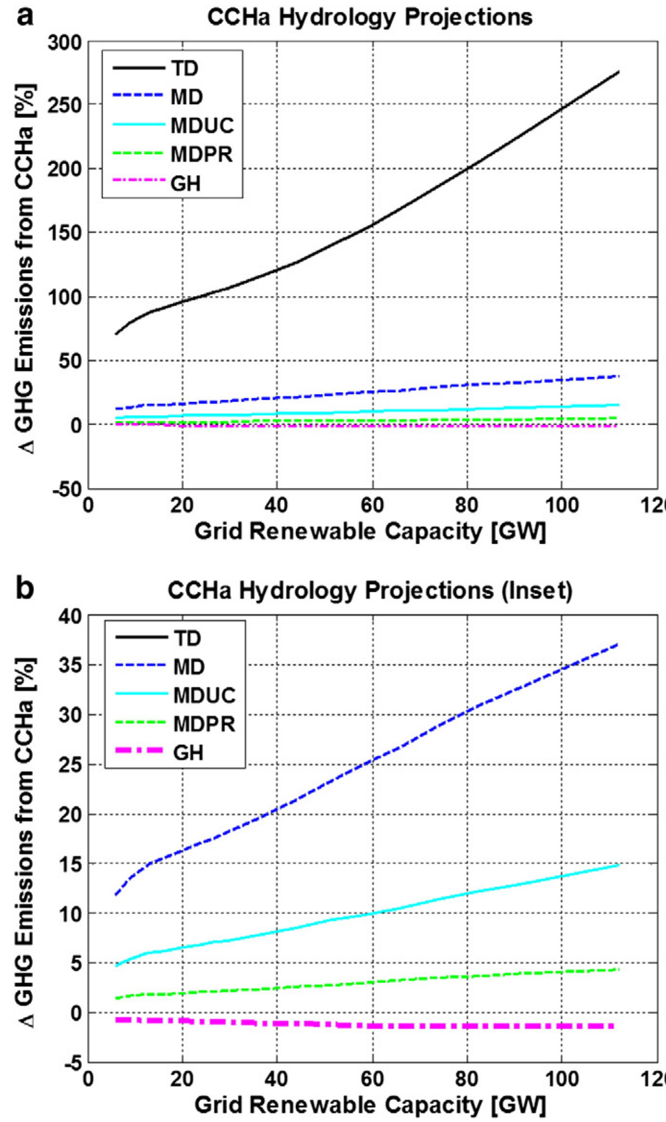

Fig. 12. Change in greenhouse gas emissions from the no-option case under climate change augment conditions as a percentage of the no-option case value vs. grid renewable capacity.

greenhouse gas emissions except for the GH case. Recall that all of the cases except for the TD case require some amount of membrane desalination, which increases the electric load demand, since other measures are insufficient to stabilize reservoir levels alone under these conditions. Additionally, the scale of the required technologies is also much larger, imposing larger loads on the grid compared to the baseline case. Similar to the baseline case, thermal desalination demonstrates significantly increased GHG emissions compared to the base case.

All of these cases do not show the inverted behavior at high renewable capacities demonstrated in the baseline case results, since growth in the electric load demand does not allow large amounts of excess renewable generation to be present.

The GH case, which represents the water supply stabilization portfolio configured for the lowest possible greenhouse gasses, is able to marginally reduce the greenhouse gas emissions compared to the no-option case under these conditions. This mix heavily uses urban water conservation, available water reuse, and uses only the minimum amount membrane desalination needed to stabilize the reservoir levels. This demonstrates that even with increases in demand and reductions in reservoir inflow, surface water reservoir levels can potentially be stabilized with little to no impact on greenhouse gas emissions, and emphasizes the importance of careful selection. Recall that when examining water goals alone in Part 1, urban water conservation had a slightly smaller incremental effect as water reuse due to its spatial distribution, and less overall potential. On the basis of energy goals, however, it is the best option and should be utilized as much as possible, with other options taking decreased priority.

4.4. Renewable energy utilization impacts of securing water availability

California, as well as other states and entities, have set targets for the utilization of renewable energy on the electric grid known as renewable portfolio standards (RPS). Many analyses have focused on the deployment of renewable capacity to meet this target assuming load growth due to population only. This assumption is based on the composition of the electric load demand being relatively static in the future. However, many options for meeting the sustainability goals of other resource sectors such as have effects on the electric load. Depending how these options are deployed, their presence can change the composition and magnitude of the electric load in ways not currently taken into account in RPS analyses.

The water supply sector is one such resource sector, along with transportation. The effects of transportation options on the ability to meet RPS goals have been examined by Tarroja et al. (2014). This analysis focuses on the effect of taking different pathways to secure surface

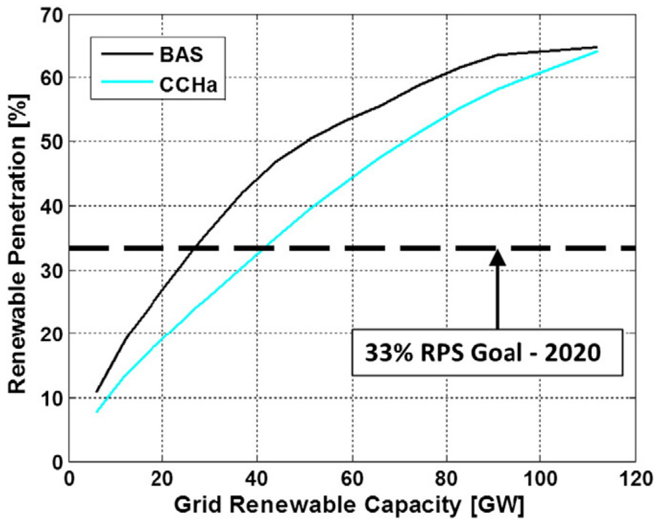

Fig. 13. No-option grid renewable penetration vs. grid renewable capacity for baseline and climate change augment conditions.

reservoir levels on the ability to meet renewable portfolio standards in the region.

Fig. 13 shows the grid renewable penetration as a function of installed renewable capacity, using the renewable mix specified in this study. The dotted line shows the current RPS goal in California (Anon., 2009b), which targets a 33% renewable penetration by energy by the year 2020.

Under baseline conditions, the renewable penetration initially increases linearly with installed capacity, however, it tailors off at high renewable capacities due to curtailment of excess renewable generation. This trend has been studied in detail by Tarroja et al. (2011) and Eichman (2012).

Under climate change augment conditions, more installed renewable capacity is required to meet the same renewable penetration level. This primarily occurs due to the growth of the electric demand caused by population. Therefore, more renewable capacity is required to meet a given percentage of the load demand.

The effect of the successful water option portfolios on the grid renewable penetration level relative to the no-option case for baseline conditions is presented in Fig. 14. Note that this is presented as a change from the no-option value vs. the no-option case value. For example, at a 10.7% no-option (base) renewable penetration, the GH case increases the renewable penetration by 2.4%, resulting in an actual renewable penetration of 13.1%.

For most of the range of renewable capacities considered here, three of the portfolios (PR, MDUC, GH) tend to increase renewable energy utilization while the desalination-only portfolios tend to decrease it (TD, MD). This occurs due to the fact that the PR, MDUC, and GH portfolios tend to remove load from the electric grid, allowing a given renewable capacity to serve a larger fraction of the overall electric load. These cases increase the renewable penetration by up to 2.5%, 2.0%, and 0.9%, respectively. This indicates that using these portfolios to stabilize surface reservoir levels can aid in helping achieve renewable portfolio standard goals. The TD and MD cases, conversely, do the opposite by imposing electric load, reducing the renewable penetration level by up to 1.0% and 3.3%, respectively, potentially providing difficulty in helping the state meet renewable portfolio standard goals. Membrane desalination has the largest negative effect, since it imposes the largest electric load on the grid.

At higher renewable capacities, the effect of these different paths is reduced and even reverses at the very high end of the range. This occurs since the load-adding technologies are able to use excess renewable generation that would otherwise be curtailed, increasing the overall energy fraction of the load served by renewables. Conversely, load-reducing technologies in this part of the range can remove electric load at times where it would have been served by high renewable generation, decreasing the overall renewable penetration.

It is important to note, however, that in the real-world system, water supply measures will not have the exclusive rights to use excess renewable generation. Other loads such as that due to electric vehicles, hydrogen electrolysis, or technologies such as energy storage all benefit from the use of excess renewable generation, however, how excess generation will be distributed between all of these loads will is an important, but open, question that is beyond the scope of this analysis. Therefore, the reversal in behavior between the portfolios should be viewed within context.

The effect of the successful water option portfolios on the grid renewable penetration level relative to the no-option case for climate change augment conditions is presented in Fig. 15.

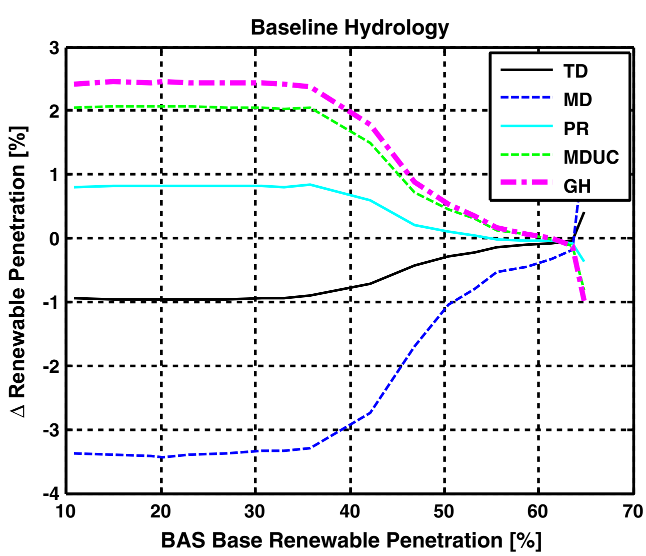

Fig. 14. Change in renewable penetration from no-option case vs. no-option renewable penetration level—baseline conditions.

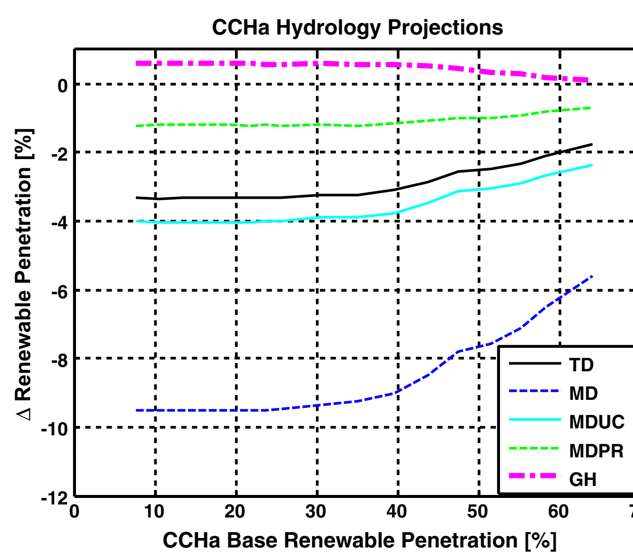

Fig. 15. Change in renewable penetration from no-option case vs. no-option renewable penetration level—climate change augment conditions.

Due to the scale of the options required to stabilize water reservoir levels, most of the option portfolios add load to the electric grid, with the exception of the GH case. The MDPR, TD, MDUC, and MD cases reduce the renewable penetration by up to 1.2%, 3.3%, 4.0%, and 9.6%, respectively. At low base renewable penetration levels, securing water availability will hinder the ability of the electric grid to meet RPS goals to different extents, requiring even more renewable capacity to be installed. This is especially true of the membrane desalination only case, which will require large increases in renewable capacity to meet a given renewable penetration level.

The GH case, where water stabilizing options are chosen based on minimizing combined system greenhouse gas emissions, has a slightly beneficial impact on the ability of the system to meet RPS goals, but is mostly neutral.

Under these conditions, the decrease of the effect of installing the load-adding portfolios is also due to the use of otherwise curtailed renewable generation. Since the raw electric load demand is much larger under these conditions, excess renewable generation is not as prevalent.

Major climatic extremes such as the 2014 California Drought (AghaKouchak et al., 2014) could lead to changes in water policy and hence, water availability or pricing. Furthermore, extreme events could result in short-term or long-term changes in the water cycle and water security as well as energy consumption. Several studies have showed that climate extremes have increased in the western United States and California (Hao and AghaKouchak, 2013; Damberg and AghaKouchak, 2013) and may continue to change in future (Seager et al., 2007). The results of this study are based on historical observations and climate model simulations and current policies in place. This paper does not provide recommendations for water–energy sustainability under a specific climate extreme condition (e.g., a certain prolonged drought). Understanding water–energy nexus for specific extreme conditions warrants future in-depth research.

5. Conclusions

The effects of implementing options to stabilize surface reservoir levels on greenhouse gas emissions and the ability to meet renewable energy utilization goals were conducted for the California water–electricity system, under baseline and climate change augment inflow conditions. The key conclusions of this study are as follows:

1. Greenhouse gas emissions increase due to reduced hydropower generation under climate change augmented conditions. Reduced reservoir inflow decreases the energy contribution of hydropower towards serving the load demand and its ability to provide grid reliability services. This conclusion is similar to those from studies by Madani et al. (2014), Guégan et al. (2012), and Blasing et al. (2013). This must be compensated for by natural-gas power plants, which produce emissions. This effect is small, however, relative to emissions increases due to demand growth.
2. Emissions effects due to systematic impacts of implementing options must be taken into account. When emissions effects due to impacts on electric loads due to conveyance, treatment, distribution, and wastewater treatment are taken into account for each option, the greenhouse gas emissions intensity maybe very different compared to evaluating direct and process-based emissions alone.
3. For this system, the priority of available options from a greenhouse gas emissions perspective is as follows:
   - Urban water conservation
   - Water reuse
   - Thermal desalination with waste heat
   - Membrane desalination
   - Thermal desalination with direct natural gas

   In Part 1, however, it was discovered that the lowest emissions options are limited in potential capacity. Urban water conservation was limited around the 2–3 Mm^3/d range, water reuse around the 18.4 Mm^3/d range (theoretical), and thermal desalination with waste heat about 3.6 Mm^3/d. These limitations are sourced from either technical operation or economic constraints. Under baseline hydrological conditions, individual options were found to be capable of securing water availability. Under climate change hydrological conditions, however, the low-emissions options were exhausted and still unable to stabilize water availability, requiring that higher emission options be implemented to stabilize the water supply.
4. Reservoir levels may be secured with beneficial or neutral effects on greenhouse gas emissions if the portfolio of water supply stabilizing options is chosen carefully. Under baseline conditions, it was shown that certain portfolios actually reduced greenhouse gas emissions compared to the no-option case. Under climate change augment conditions, a carefully selected portfolio of measures can stabilize reservoir levels with no net effect on greenhouse gas emissions.
5. Securing water availability can either be detrimental or beneficial for progress towards satisfying renewable portfolio standard goals, depending on portfolio composition. Under baseline conditions, successful portfolios changed the grid renewable penetration level by between −2.5% and +3.3%, while under climate change augment conditions, this range is altered to between −9.6 and +0.7%.

Overall, there are many criteria which must be considered when planning a strategy to meet both goals of stabilizing water supplies and reducing greenhouse gas emissions simultaneously. Certain options perform well on one criterion, but may not do so on another. Additionally, certain options are physically limited in their ability to contribute to satisfying either goal. Practical, implementation, and social challenges are also strong factors in influencing these strategies, and coordinated management of water supplies must be present to take advantage of identified synergistic interactions between the electricity and water supply sectors.

One aspect that this study did not address, however, was optimization of the renewable rollout mix with respect to water impacts and feedbacks within the water–energy nexus context. This study utilized a single renewable rollout strategy as determined by current policies and projections, however, utilizing different renewable mixes moving forward can affect the scale of water supply stabilization options needed to secure water availability. Certain renewable types such as solar thermal and geothermal power consume high volumes of water per unit of energy produced even relative to conventional power plants. In the case of the former, high solar thermal potential regions also coincide with areas of the state that have low water availability and a strong reliance on already-stressed groundwater resources. Other renewable types such as wind and solar photovoltaic, however, have significantly lower water consumption relative to conventional power plants, and reliance on these types can have co-benefits for securing water availability. This is a topic of ongoing and future work within our group.

This study was aimed at providing some quantitative insight into how available options perform based on different criteria. While many criteria have not been evaluated or are not quantifiable, the results of both Part 1 and Part 2 of this study provide some direction for policy planners to develop strategies for option deployment to satisfy sustainability goals. Evaluation of these options on the basis of additional criteria and further exploration of the implications of these results are subjects for future work.

Conflict of interest

None.

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