

Impacts of Groundwater Constraints on Saudi Arabia's Low-Carbon Electricity Supply Strategy

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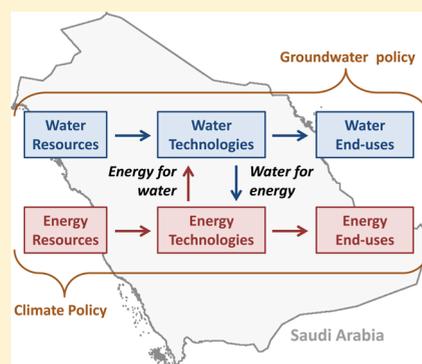
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Supporting Information

ABSTRACT: Balancing groundwater depletion, socioeconomic development and food security in Saudi Arabia will require policy that promotes expansion of unconventional freshwater supply options, such as wastewater recycling and desalination. As these processes consume more electricity than conventional freshwater supply technologies, Saudi Arabia's electricity system is vulnerable to groundwater conservation policy. This paper examines strategies for adapting to long-term groundwater constraints in Saudi Arabia's freshwater and electricity supply sectors with an integrated modeling framework. The approach combines electricity and freshwater supply planning models across provinces to provide an improved representation of coupled infrastructure systems. The tool is applied to study the interaction between policy aimed at a complete phase-out of nonrenewable groundwater extraction and concurrent policy aimed at achieving deep reductions in electricity sector carbon emissions. We find that transitioning away from nonrenewable groundwater use by the year 2050 could increase electricity demand by more than 40% relative to 2010 conditions, and require investments similar to strategies aimed at transitioning away from fossil fuels in the electricity sector. Higher electricity demands under groundwater constraints reduce flexibility of supply side options in the electricity sector to limit carbon emissions, making it more expensive to fulfill climate sustainability objectives. The results of this analysis underscore the importance of integrated long-term planning approaches for Saudi Arabia's electricity and freshwater supply systems.



INTRODUCTION

Located on the Arabian Peninsula in Western Asia, the Kingdom of Saudi Arabia is a rapidly expanding economy of more than 28 million people. From 1990 to 2010, the average income in Saudi Arabia nearly doubled,¹ and was accompanied by an average annual increase in urban electricity and freshwater demand of 7 and 3%, respectively.^{2,3} With similar demographic trends projected moving forward,^{4,5} there is concern surrounding increased consumption. The additional strain on the region's existing infrastructure will require expanded electricity and freshwater supply capacity.^{3,6,7} A key challenge facing regional planners is identification of a cost-effective and sustainable long-term development strategy.

Compared to most other nations, Saudi Arabia contains relatively little exploitable surface water, and relies primarily on groundwater resources for its freshwater supply.³ Annual groundwater withdrawals of approximately 18 km³ exceed the estimated national renewable groundwater resource of 0.8–2.2 km³, and are rapidly depleting long-term aquifer storage in the region.^{3,8–10} To mitigate the risk of freshwater scarcity, the country has developed more seawater desalination capacity

than any other nation globally.^{10,11} Wastewater recycling also plays an important role in managing the region's freshwater challenges.^{10,12} As desalination and wastewater recycling requires more electricity than conventional groundwater and surface water supply technologies,^{13,14} expanding capacity to balance groundwater constraints and urban growth will impact the regional electricity supply.

The bulk of electricity generation in Saudi Arabia is from oil burning thermal plants (53% in 2010²) that are carbon intensive. Increased electricity demand from the water sector thus exacerbates climate change risks. The region has abundant untapped renewable energy resources in the form of favorable solar, wind, and geothermal energy potentials.^{15–21} To meet increasing demands while decreasing carbon emissions, national energy policy calls for the development of over 50 GW of new renewable electricity generation capacity by 2040.^{22,23}

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Increased operational flexibility will support legislated solar and wind power integration, and is an electricity service market well-suited for an electrified freshwater supply.^{24–26} Thermal power plants can also require large amounts of freshwater for cooling and steam production,²⁷ although regional freshwater scarcity has prompted implementation of alternative seawater and air cooling technologies throughout Saudi Arabia.^{28–30} Trade-offs with conventional freshwater cooling systems include increased implementation and maintenance costs, and reduced power generation efficiency.^{31–33}

The existing linkages between Saudi Arabia's electricity and freshwater strategies, and the pressing need for a transition toward a more sustainable pathway, make an integrated electricity-freshwater supply strategy essential. A number of previous studies highlight cobenefits of systems integration. Analysis of regional technology deployment strategies find that solar-assisted desalination is already cost-effective in many locations throughout Saudi Arabia for the combined supply of low-carbon electricity and freshwater services.^{16,19} Opportunities to enhance operational efficiencies in coupled electricity-water supply systems through combined management have also been investigated for similar arid regions in the Middle East.^{24,34} Recent analysis has also focused on the climate impacts of various water supply options in the U.S. under predefined electricity supply scenarios.³⁵ Less explored are the interactions between electricity and freshwater systems during the planning of regional infrastructure capacity (supply technologies and networks). These investment decisions are important from the viewpoint of policy, as electricity and water supply infrastructures last for many decades and introduce structural inertia into the long-term development pathway.³⁶ This quality of energy and water infrastructure requires prospective analysis of development strategies over decadal time-scales.^{8,36}

Optimization models have emerged as key planning tools that enable system designers to explore long-term development pathways and the trade-offs among technology options.^{37,38} Many regional jurisdictions employ optimization models to develop integrated resource plans,³⁹ and yet few combine long-term energy and water supply planning despite potential synergies. For example, previous research demonstrates that water supply planning models are sensitive to energy prices,^{37,40,41} and likewise electricity generation planning models are sensitive to water constraints,^{42–46} and water-related energy demand.^{6,26,47} Recent analysis of the Middle East region and China at a relatively coarse spatial and temporal resolution demonstrates the insights from and benefits of co-optimizing electricity and freshwater supply planning decisions.^{48–50} This type of *hard-linked* optimization framework allows identification of pathways that hedge against undesirable interactions between electricity and freshwater systems, and provides a platform to explore technology portfolios that simultaneously balance energy and water sustainability objectives. Similar research underscores the importance of geography due to water distribution-related energy costs.⁴⁷ These spatial effects are particularly important to consider in the case of Saudi Arabia because of the inland urban population lacking direct access to desalination opportunities available on the coast.

In this paper, we develop a modeling framework that co-optimizes electricity and freshwater supply planning decisions across spatially distributed regions to provide an improved representation of feedbacks between coupled infrastructure

systems. The tool is applied to study impacts of groundwater management on the structure of the electricity system and the potential interplay with strategies aimed at reducing electricity sector climate impacts through deployment of low-carbon power generation. Results of this analysis provide important insight into the potential cost of policies and characteristics of technology portfolios that enable a transition toward a more sustainable system.

■ MATERIALS AND METHODS

We explore the interaction between long-term groundwater constraints and climate change mitigation objectives with a linear systems-engineering optimization model. We provide an overview of the salient features of the model in this section; the mathematical details are given in the [Supporting Information \(SI\)](#) (section S1 to S3). The modeling framework explicitly represents key electricity and water supply technologies in Saudi Arabia. Each technology is modeled as a linear input–output process where the consumption of resources and production of services are defined by average conversion factors. Technologies are coupled to form a closed system by accounting for the physical balance of resources across the modeled supply chain. A cost-optimization model calibrated to the existing national electricity and freshwater supply systems is then used to identify future infrastructure investments under projections of future demand and technology costs. The framework is applied across a number of scenarios to explore sensitivities to different national policy levers and model parametrizations.

Integrated Systems Modeling. The integrated systems model developed for the analysis is depicted in [Figure 1](#). The supply systems are mapped as a series of electricity and water flows between technologies. The system boundary is defined such that hydro-climate data is used to parametrize water resource constraints, including the availability of surface water, groundwater and precipitation. Sector demand projections parametrize supply requirements. The water supply technologies included are reverse osmosis (RO) desalination, multistage flash (MSF) desalination, rainwater harvesting, groundwater withdrawals, and surface water withdrawals. These technologies convert raw water resources (seawater, precipitation, groundwater and surface water) into freshwater suitable for consumption within the different end-use sectors (agriculture, industrial and domestic). Water storage technologies included are surface reservoirs and potable water storage at end-use. Wastewater recycling is also included in the analysis, and enables upgrading of wastewater to potable quality. Water supply technologies interact with the electricity system through electricity intensity factors (e.g., kWh per m³ of potable water produced). The cost and energy intensity of water supply technologies are parametrized to include pretreatment and local distribution ([Supporting Information, Table S4](#)).^{13,14,51} Thermal energy requirements for MSF desalination technologies are also included and are supplied with the estimated excess heat from colocated thermal power generation, which is a common practice at modern combined-cycle plants in Saudi Arabia today.⁵²

Modeling of the electricity supply system parallels that of the water supply, and considers a number of different power plant technologies. Fossil fuel technologies (oil or natural gas) included are single- and combined-cycle steam turbines, and combustion turbines. We exclude carbon capture and storage technologies due to uncertainties surrounding costs and

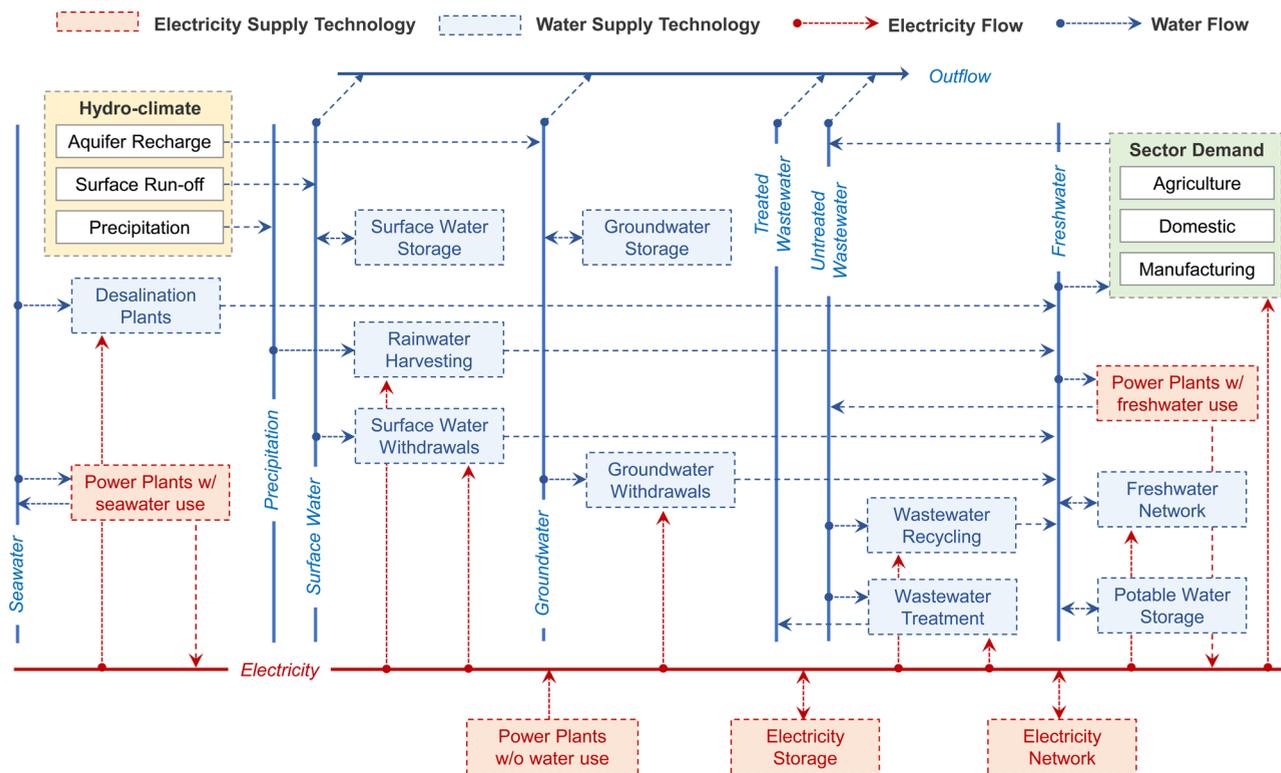


Figure 1. Integrated modeling of electricity and water supply systems. The systems are mapped as a series of flows between technologies. Each technology is modeled as a linear input-output process where the consumption of resources and production of services are defined by average conversion factors. Technologies are coupled to form a closed system by accounting for the physical balance of electricity and water flows across the modeled supply chain. The system boundary is defined such that existing hydro-climate data is used to parametrize water resource constraints, including the availability of surface water, groundwater and precipitation. Exogenous sector demand projections (manufacturing, domestic, and agriculture) parametrize supply requirements. The integrated system is represented in each province, with the network technologies allowing flow and trade of electricity and freshwater between provinces.

performance. Coal is also excluded due to its high emission intensity and expected impact on regional energy security (international imports would be required). Low-carbon technologies considered include nuclear, municipal waste-to-energy, geothermal, onshore wind, solar photovoltaic (PV), and concentrating solar power (CSP) with and without thermal storage. Thermal power plants (including CSP) are further distinguished by cooling technology to enable feedbacks to the water supply system. Once-through and closed-loop cooling systems utilizing freshwater are considered in the analysis, as well as air-cooled and seawater-cooled once-through systems. The volume of water withdrawn and the associated wastewater return flow is defined based on average water intensity factors (i.e., m³ of water per kWh generated).⁵³ The choice of cooling system affects operating efficiency and investment costs,^{31–33} and these characteristics are explicitly included in the analysis by defining unique parameters for each type of cooling technology.

Constraints on peak and flexibility requirements of the electricity technology portfolio are defined to reflect operating constraints occurring between model periods (SI, section S1).⁵⁴ We also distinguish flexible and base-load power plant operational modes to account for different operating costs and scheduling procedures that accompany flexible operation.⁵⁵ Short-term electricity storage and load control technologies are also included in the analysis, and interact with the system by providing peak and flexibility reserve capacity.⁵⁶ The potential for load control is dynamically linked to the total demand for

electricity, allowing increased demand from the water sector to contribute to load control capabilities. The load control technologies are different from end-use conservation measures, which are addressed in the scenario analysis.

Long-distance transport of electricity and water is important to consider when comparing options for supply development.^{57–59} We incorporate spatial effects by disaggregating the study region into the 13 provincial administrative regions (SI, Figure S6). We chose this level of spatial disaggregation due to limited input data and computational efficiency. Expandable electricity and freshwater transmission between regions is included in the model with a simplified transport representation (i.e., the capacity of a network pathway is defined as a maximum amount of water or electricity that can be transferred over a given model period). Transmission losses are included (SI, Table S7). Energy for interprovincial water conveyance is estimated based on a recent analysis of long-distance desalination transport in the United States,⁶⁰ and incorporates vertical and horizontal components of expected energy use (SI, S1.2). Distances and elevations between regions are inferred based on the locations of major provincial cities, with primary road transport connecting these cities used as a proxy for candidate network pathways. Elevation distances are calculated based on the altitude of major cities and do not incorporate the cumulative elevation change.

Although the majority of Saudi Arabia’s population resides in urban areas (82% in 2010¹), there remains a significant rural population. These individuals often lack access to the urban

electricity and water supply infrastructures. We model the rural technologies separately to reflect these differences, with limitations set on the availability and cost of options. Rural electricity technologies considered in the model include diesel generators, solar PV and battery storage systems. For freshwater, rural areas are assumed to have access to groundwater, rainwater harvesting, and wastewater recycling technologies.⁶¹ Anticipated urbanization is included in the demand projections, allowing the analysis to address future migration toward urban areas. Electricity and freshwater trade between rural and urban areas is excluded.

Optimization. Optimization methods are used to solve for the capacity (design) and output (activity) of technologies included in the model (SI, section S1). The objective of the optimization is to minimize cumulative discounted costs of water and electricity supply systems over the planning horizon, with technology investment, fixed/variable O&M, and fuel costs considered in the system cost accounting. This type of cost-optimization model is common in national infrastructure planning,^{38,39} and could be extended to include risk metrics or multiobjective formulations. Similar to the approach proposed in Dubreuil et al. (2013),⁴⁸ we represent both water and electricity supply technologies and solve for the design and activity variables simultaneously. Climate and groundwater objectives are modeled as constraints on carbon emissions and groundwater withdrawals. A planning horizon of 2010–2050 in 5-year segments is selected for the analysis to explore impacts of national policy and path-dependency on technology deployment. Each modeled year is broken into monthly time-slices to enable treatment of seasonal effects, such as the potential mismatch between available supply and demand. Intertemporal optimization is used to solve for each time-step concurrently.

Parameterization. A significant amount of input data is required to parametrize the model, and is detailed in the SI (section S2). We specifically calibrate the model to existing conditions by identifying the capacity, vintage, and location of existing and committed infrastructure from regional planning documents and recent resource assessments (SI, Tables S3, S5 and S8).^{6,10,13,28,29,62–64} Cost and performance data for supply technologies are taken from a number of recent technology assessments (SI, Tables S2, S4 and S7).^{13,14,51,53,61,65–71} Future fuel costs are estimated using domestic prices from a previous regional planning study,⁶ and growth rates for the Middle East North Africa (MENA) region projected from a global integrated assessment model.⁷² Due to regional water scarcity and lack of data, we assume that all thermal power generation in 2010 located in coastal regions are seawater-cooled and all thermal generation in 2010 located inland are air-cooled. Technical documentation for large-scale plants support this assumption.^{28–30}

Demand Projections. Demands for electricity and water from the coupled supply technologies are endogenous to the cost-optimization model. Limited data is available to parametrize the diverse set of technologies and consumers existing in the domestic, agriculture, and manufacturing sectors. We therefore treat these demands as exogenous and define a number of scenarios to explore uncertainties surrounding conservation potential. Econometric models linking socio-economic development to consumption are typically used to generate exogenous electricity and freshwater demand projections,^{6,16,39} and we apply a similar approach to generate demands for Saudi Arabia. The demand models estimate

agriculture, manufacturing and domestic electricity and freshwater consumption based on projected population, urbanization, GDP and rate of technological change (i.e., improved efficiency over time). The model identification process and parametrization is summarized in the SI (section S3). Corresponding wastewater volumes from the industrial and domestic sectors are estimated with national consumption efficiencies (the fraction of water withdrawn that is consumed) from a previous global analysis.⁷³

For the projections, we use population, urbanization, and GDP trajectories aligned with the shared socioeconomic pathways (SSP).^{4,5,74,75} We specifically focus on the SSP2 scenario, a midrange case reflecting a continuation of current trends (moderate sustainability policy and technology shifts). Although SSP2 is a moderate scenario (globally), in the specific case of Saudi Arabia it corresponds to substantial population and economic activity growth.^{4,5} We utilize the quantitative SSP scenario data to generate a reference national-level electricity and freshwater demand trajectory for each sector (agriculture, manufacturing, and domestic) out to 2050. The results are depicted in Figure 2 and project an average annual growth rate for urban electricity demand of 3%. The trajectories are more conservative than other recent projections,²² and suggest the existing renewable energy deployment strategy (50 GW by 2040) will accommodate load growth and not reduce aggregate electricity sector emissions.

Water demands remain relatively constant reflecting large reductions in per capita irrigation. Nevertheless, desalination would be needed to support the reference irrigation demand under aggressive groundwater conservation, which represents a significant and costly transformation pathway. Similar development has occurred in Spain and Israel, where the desalinated seawater enables production of high-value fruits and vegetables in areas facing water scarcity.⁷⁶ Recent analysis of Saudi Arabia's agricultural policy suggests a shift toward increased production of similar crops to promote national food security.⁷⁷ It therefore seems likely that Saudi Arabia would consider large-scale seawater desalination as a potential supply option for irrigation.

When desalinated seawater or recycled wastewater is used for irrigation, additional care must be taken to replace nutrients stripped during the treatment process that are important for soil quality.^{78,79} These additional costs are excluded from the assessment due to lack of data.

The estimated national domestic and industrial demands are downscaled to the provincial level based on the population distribution, whereas agriculture demands are disaggregated following the historical provincial distribution.⁸⁰ Future monthly domestic electricity demands are decomposed based on historical trends.²² Domestic and irrigation water demands are broken into monthly components based on the estimated monthly average soil moisture deficit, which is calculated across $\frac{1}{4}$ degree grid cells and weighted based on population for domestic demands.⁸¹

Scenarios. The model is applied across a number of scenarios to explore: (1) trade-offs and synergies between groundwater and climate policy; and (2) sensitivity to uncertainties in model parameterization. The impact of national groundwater policy on the electricity and freshwater supply systems is explored by varying the allowable annual extraction in each model region. It is estimated that at current extraction rates approximately 50 years of fossil groundwater remains in Saudi Arabia,^{13,82} although estimates vary widely across the

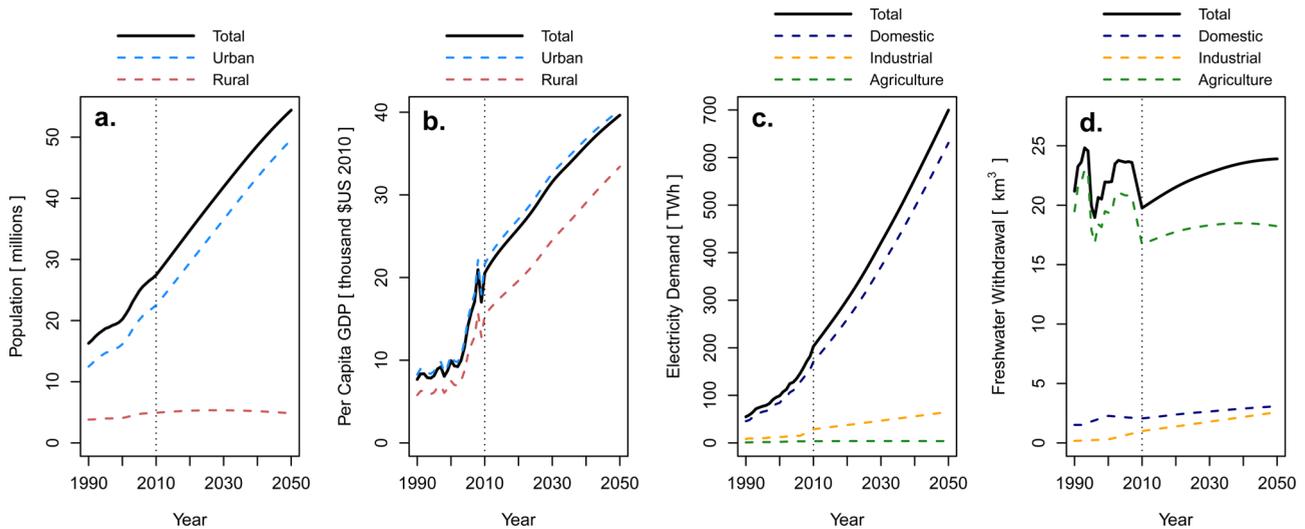


Figure 2. National socioeconomic and demand projections for the SSP2 scenario. a. Population; b. Per capita GDP in purchasing power parity (PPP); c. Electricity demand; and d. Freshwater withdrawal. Industrial demands exclude electricity for desalination and cooling water for thermoelectric generation.

literature.¹⁰ We initially explore the midcentury time frame by constraining the allowable extraction in each region along a linear trajectory that results in national annual groundwater withdrawals reducing from 18 km³ in 2010 to 1.6 km³ in 2050 (i.e., a 91% reduction). This would correspond to an annual extraction rate in 2050 that falls within estimates of the renewable recharge.^{10,80} This also corresponds to a depletion of remaining nonrenewable groundwater reserves of approximately 330 km³ by 2050, which is within recent estimates of the available resource.¹⁰ It is important to note that further investigation into the distributed aquifer response via long-term hydrogeological modeling should be pursued to fully understand the implications for groundwater sustainability.^{8,83}

We also explore potential interplays with increasingly ambitious climate policy. Limiting 21st century climate change to 2 °C over preindustrial levels will require widespread transformation of the electricity system.⁷² We construct scenarios for Saudi Arabia by simulating stringent mitigation policies that are constrained to achieve an 80% reduction in cumulative carbon emissions as compared to unconstrained conditions by the year 2050. Sensitivity to simultaneous groundwater and climate objectives are then examined by simulating different combinations of increasingly stringent policy scenarios. Each policy objective is varied between a baseline (0% fulfillment) and a 100% fulfillment case in increments of 50%. As groundwater is already overexploited, the baseline constrains withdrawals to 2010 levels. The results of this analysis provide insight into how costs and technology deployment patterns vary based on groundwater and climate policy ambition.

To investigate results sensitivity to uncertain model parameters, the cost-optimization model is applied across the scenarios listed in Table 1. The *Reference* scenario considers average performance parameters and the exogenous demands depicted in Figure 2. Uncertainties surrounding the scale of the available groundwater resource are explored by parametrizing a conservative scenario that shifts the 91% reduction target to the year 2030. An additional scenario considers a 50% capital cost subsidy to renewable electricity generation, and is meant to reflect a situation where market conditions are improved with

Table 1. Summary of Scenarios Explored in the Analysis

scenario	model implementation
reference	reference demand trajectories, performance/cost parameters follow averages from the literature
2030 groundwater target	the groundwater target year is shifted from 2050 to 2030
low-cost renewables	investment costs for renewables are reduced by 50% relative to the reference scenario
water conservation	exogenous freshwater demands are reduced by 40% in 2050 relative to the reference scenario
electricity conservation	exogenous electricity demands are reduced by 40% in 2050 relative to the reference scenario
increased food imports	agriculture freshwater withdrawals are reduced by 50% relative to the reference scenario
efficient water supply	water supply technologies set to the lowest energy intensity from the literature
optimistic	electricity and water conservation, increased food imports and efficient water supply

external financial support. The remaining scenarios explore demand uncertainties. Although the reference demand trajectories include improvements in energy efficiency, advanced conservation scenarios are defined to reflect uncertainties surrounding technological change, price response, and end-use behavior (SI Figures S2 and S3). Exogenous demands in the advanced conservation scenarios decrease 40% by the year 2050 relative to the reference scenario. This represents a potential for water and electricity conservation similar to that identified in recent analyses.^{13,47,84,85} The potential impacts of alternative food import policies on national irrigation withdrawals are also important to consider due to the fraction of total freshwater demand applied for irrigation. We explore a scenario investigating the potential for increased food imports to displace unconventional water resource expansion by simulating a 50% reduction in irrigation withdrawals by 2050 (SI Figure S4). The electricity intensity of water supply technologies is also uncertain, and we explore the potential for enhanced performance to impact the results by including a scenario parametrized with the lowest energy intensities from the literature (SI Table S4). Finally, we combine all

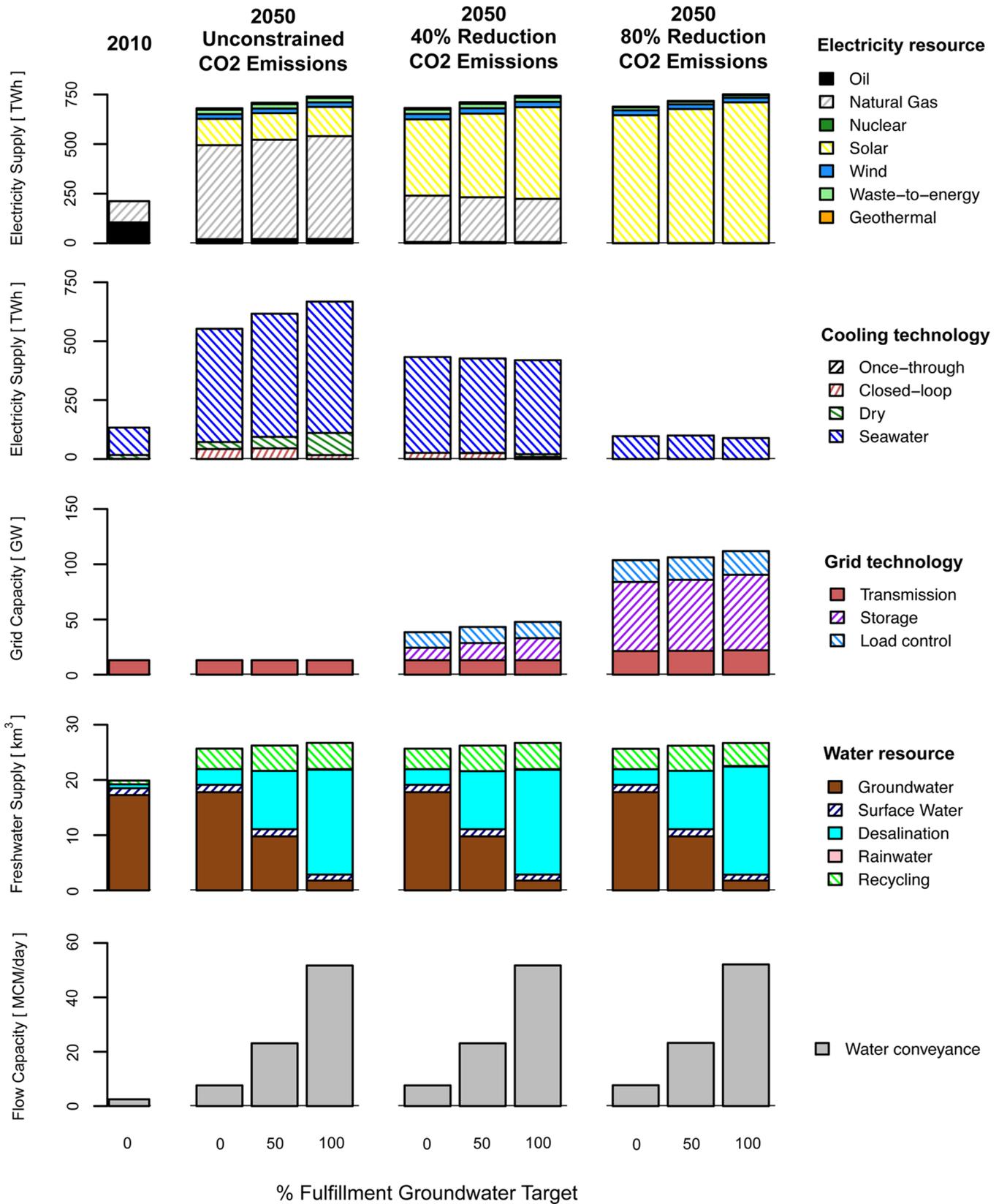


Figure 3. Optimal supply mixes and network technology capacities aggregated to the national-scale for the year 2020 across the groundwater and climate policy objectives investigated. The groundwater target represents a 91% reduction in annual groundwater withdrawals in 2050 relative to 2010.

conservation measures and efficient water supply assumptions to generate an *Optimistic* development scenario (SI Figure S5).

All scenarios include Saudi Arabia’s existing renewable energy deployment strategy that involves integration of over 50 GW of

renewable power generation by 2040. The strategy includes the following technology-specific targets: 25 GW of CSP, 16 GW of solar PV, 9 GW of wind, 3 GW of waste-to-energy, and 1 GW of geothermal.²² We model this policy by constraining the capacity from the associated technologies to exceed an annual deployment target in each simulated year. The target capacity development represents a linear trajectory fitted between current levels and the 2040 goal.

RESULTS

We initially focus on analyzing the implications of simultaneous groundwater and emission constraints on supply and network technology development for the *Reference* scenario. Depicted in Figure 3 are the optimal supply mixes and network technology capacities aggregated to the national-scale for the year 2050 across the groundwater and climate policy objectives simulated. Provincial results are included in the SI (section S4.2).

The rapid growth in electricity demand and retirement of existing units results in a complete redesign of the electricity generation portfolio. When carbon emissions are unconstrained, combined-cycle natural gas plants makeup the largest portion of new capacity due to the relatively low investment cost. The capacity is deployed primarily in coastal regions to access seawater for cooling. A relatively small amount of capacity employing closed-loop freshwater cooling is also deployed in Asir: a province lacking coastlines but with a relatively high per capita availability of surface water resources. Air-cooled combined-cycle generation and combustion turbines are deployed in the remaining provinces to help support load growth without expanding transmission. Existing renewable energy policy (50 GW of installed capacity by 2040) results in wind, geothermal, solar PV, and CSP expansion. The CSP capacity is deployed in coastal regions due to the accessibility of seawater for cooling. Rural areas combine diesel generators with PV capacity to meet the stagnating demand growth anticipated under the SSP2 urbanization scenario. The constraint on groundwater withdrawals in the reference case to remain at or below 2010 levels results in an increase in wastewater recycling and desalination capacity, and expansion of the water conveyance infrastructure beyond 2010 levels is needed to transport desalinated water inland.

Policy that reduces cumulative carbon emissions in 2050 by 80% relative to the unconstrained scenario triggers an electricity system transformation. All regions rapidly deploy solar technologies to reduce emissions, and utilize a combination of conventional storage and load control technologies to maintain system reliability. PV technology expands particularly quickly under the parametrized cost improvements. Seawater withdrawals reduce significantly under PV expansion due to the displacement of seawater-cooled thermal generation. Electricity transmission capacity is reinforced to support matching seasonal solar and load coincidence across provinces. The electricity system transformation is found to have a relatively modest impact on the structure of the water supply. The largest difference compared to the unconstrained emissions case is a small increase in wastewater recycling.

Policy that reduces annual groundwater withdrawals in 2050 by 91% relative to 2010 results in a significant transformation of the water supply system. RO desalination capacity expands rapidly in coastal provinces, and all regions utilize available wastewater for recycling. The interprovincial water network is developed more extensively to support inland transfer of desalinated water from coastal regions, and a greater volume of

water must be produced to overcome distribution losses. The regional distribution of electricity technologies shift toward increased capacity of power generation in coastal regions where desalination occurs. The increased electricity demand from desalination and water conveyance impacts the electricity transmission configuration, with larger capacity corridors developed between regions connecting high-quality inland solar energy resources with coastal desalination opportunities. More investment into load control technologies also occurs due to greater resource availability accompanying the increased water sector electricity demand.

In the baseline scenario (no emissions or groundwater reduction targets), water sector electricity use increases from 15 TWh in 2010 to 22 TWh in 2050 (3% of total national electricity demand). The majority of water sector electricity use in this case is from groundwater (11 TWh), with the remaining balance mainly attributed to desalination (6 TWh), recycling (3 TWh) and conveyance (2 TWh). Electricity requirements increase rapidly with stringency of the groundwater constraint. In the scenario where groundwater withdrawals are reduced by 91% in 2050, the freshwater supply sector represents 12% (92 TWh) of total final electricity demand. For perspective, this represents more than 40% of the total national electricity demand in 2010. The majority of increased electricity use comes from desalination (67 TWh), water conveyance (19 TWh) and wastewater recycling (4 TWh), with groundwater electricity demand dropping significantly (1 TWh). The freshwater allocated to the electricity system is less intuitive. Most freshwater is used in the unconstrained emissions scenario to support closed-loop cooled natural gas generation located inland, with a small amount persisting in the intermediate scenario despite increasingly stringent groundwater constraints. Nevertheless, freshwater allocated to the electricity sector in the most extreme case represents less than 1% of projected national demand across all sectors in 2050, suggesting a relatively minor role in future freshwater supply requirements.

Transitioning to 100% fulfillment of the groundwater conservation objective without climate policy results in costs increasing 46% compared to the baseline scenario. Under 2010 groundwater withdrawals, reducing cumulative carbon emissions by 80% increases discounted costs by 51%. Combining the 91% groundwater reduction and the 80% emission reduction policies results in costs increasing by 101%. The main challenge under combined policy objectives is the need to simultaneously increase electricity supply capacity to allow for increased electricity demand due to desalination, wastewater recycling and water conveyance, while decreasing carbon intensity to maintain cumulative electricity sector carbon emissions. It is important to note that some of the benefits and costs associated with these scenarios are excluded (e.g., conservation measures, climate damages, reduced air pollution, avoided water shortages, etc.).

Further sensitivity analysis is performed by examining the results obtained across the different scenarios listed in Table 1. We specifically explore uncertainties surrounding future costs by varying the technology cost assumptions across a suitable range identified in the literature (SI, Table S9).⁷⁰ Figure 4 depicts the percent change in discounted system costs relative to the unconstrained baseline scenario (i.e., no cumulative emissions constraint, groundwater extraction limited to 2010 rates, reference demand trajectories, and average cost/performance parameters for technologies). System costs increase in the

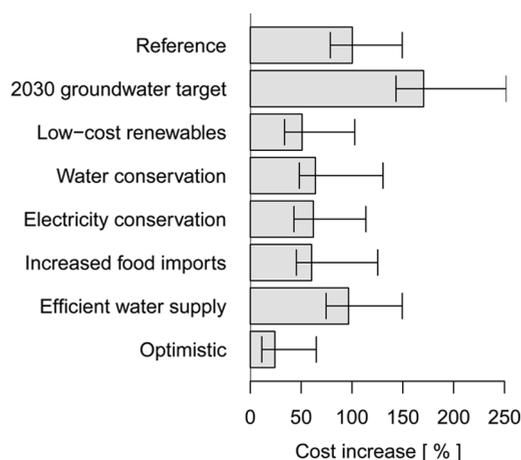


Figure 4. Sensitivity to technology cost parametrization for the scenarios listed in Table 1. The horizontal bars represent results obtained with average cost parameters. The error bars span the results obtained with the minimum and maximum cost parameters. Each scenario considers 100% fulfillment of the groundwater and climate objectives (91% reduction in groundwater withdrawals and 80% reduction in cumulative carbon emissions). The cost increase is calculated as a percent change relative to the unconstrained baseline scenario (i.e., no cumulative emissions constraint, groundwater extraction limited to 2010 rates, reference demand trajectories and average cost/performance parameters for technologies).

reference scenario between 79 and 149% relative to the unconstrained scenario. Nuclear generation expands when the least optimistic technology costs are assumed due to the slow cost improvement for solar generation and advanced grid technologies (load control and storage). Major cost savings are achieved in the "Low-cost renewables" scenario. PV and CSP become more attractive as a generating option, and expand across all regions to prevent transmission development despite the geographic diversity modeled between provinces. When the groundwater target year is shifted to a more conservative 2030 fulfillment time frame, investment into unconventional water resource options is accelerated earlier in the planning horizon, leading to large increases in system costs. The scenarios involving reduced demands achieve significant savings, whereas the enhanced water supply performance scenario displays less impact. The "Optimistic" scenario, combining the conservation and efficient water supply parametrizations, results in a supply portfolio that costs 11–65% more than the unconstrained case, thus representing considerable savings when compared to the costs obtained for the reference scenario.

DISCUSSION

Many parts of the world face increasing groundwater stress that will necessitate the deployment of alternative electricity-intensive water infrastructure, such as desalination, wastewater recycling, and long-distance water transfers. Saudi Arabia is one of the most severely constrained jurisdictions in this respect and provides a challenging case study for exploring trade-offs between electricity and freshwater systems. In this paper, we developed a new modeling framework that hard-links electricity and freshwater investment decisions across provinces to provide an improved representation of feedbacks between coupled infrastructure systems. The framework was applied to explore impacts of groundwater constraints on the structure of electricity and freshwater supply in Saudi Arabia, and the

potential interplay with climate policy aimed at reducing electricity sector carbon emissions.

Our results suggest that strategies aimed at achieving deep reductions in nonrenewable groundwater extraction will lead to fundamental changes in regional electricity system design. Large-scale expansion of desalination and regional water distribution capacity emerges as a critical infrastructure solution enabling displacement of groundwater withdrawals while supporting growth in urban freshwater demand. The required infrastructure increases water sector electricity-intensity and migrates electricity demand from distributed groundwater pumping stations to coastal desalination plants. The reconfiguration of demand benefits thermal generation, due to the ability to collocate with desalination plants and access seawater for cooling. Protecting coastal ecosystems from the increased industrial activity (e.g., thermal water pollution) will pose additional constraints to technology development that were unexplored in this analysis, and important to address in future research.

Our results further suggest that strategies aimed at mitigating nonrenewable groundwater extraction are likely to require similar investment as strategies aimed at limiting fossil fuel use in the electricity sector. The increased water supply costs follow from the required ramp-up in desalination and water distribution investments. When emission constraints are also considered, we find that higher electricity demands under groundwater constraints reduce flexibility of supply side options in the electricity sector to limit carbon emissions. The need to simultaneously increase electricity supply capacity while reducing carbon intensity make it more expensive to fulfill climate change mitigation objectives under groundwater constraints. The integrated planning framework incorporating investment and operation across provinces is crucial to identifying these trade-offs, and underscores the importance of a systems perspective when assessing suitability of supply options across the electricity-water nexus.

Results incorporating optimistic demand projections indicate the significant potential for end-use conservation to enable a low-cost transition away from nonrenewable groundwater use and toward a low-carbon electricity system. Potential policy instruments targeting demand reductions include increased prices or end-use efficiency standards. Our assessment also demonstrates the sensitivity of the optimal system configuration to uncertainties surrounding groundwater constraints and technology costs. To provide further insight into robust strategies, future work should consider endogenous representations of these key uncertainties in the optimization model. Finally, the importance of agricultural policy suggests the framework would benefit from incorporating land-use decisions. This approach would enable consideration of adaptive land management to address concerns surrounding desalination and national food security.

ASSOCIATED CONTENT

Supporting Information

This material is available free via the Internet at The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b05852.

Additional details regarding the optimization methods and input data, as well as additional scenario results (PDF)

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Notes

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