Supporting Information

Impacts of groundwater constraints on Saudi Arabia's long-term electricity supply strategy

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S1 Mathematical formulation of the supply planning model

This section presents the mathematical formulation of the supply planning model, as well as the sub-models used to estimate technology performance. The nonmenclature details the parameters and variables, with the model equations then defined.

List and description of symbols

Sets

c Carrier

m Month

m_f Final month (December)

m_i Initial month (January)

o Supply technology operational mode

r Region

rr Alternative region

s Storage technology

t Supply technology

y Year in simulation horizon

y_{end} Final year in simulation horizon

Parameters

α^{tech} Capacity used by activity in a specific operating mode

β^{tech} Maximum capacity available for an activity in a specific operating mode

δ Discount rate

$\epsilon^{net,in}$ Input activity ratio for network technology

$\epsilon^{net,out}$ Output activity ratio for network technology

$\epsilon^{sto,in}$ Input activity ratio for storage technology

$\epsilon^{sto,out}$ Output activity ratio for storage technology

ϵ^{tech} Input/output activity ratio for supply technology

γ^{net} Network technology fixed costs

γ^{sto} Storage technology fixed costs

γ^{tech} Supply technology fixed costs

μ Minimum run-time fraction for supply technologies.

ϕ^{net} Capacity or load factor of network technology

ϕ^{sto} Capacity or load factor of storage technology

ϕ^{tech} Capacity or load factor of supply technology

π^{tech} Supply technology fuel costs

ψ^{net} Network technology investment costs

ψ^{sto} Storage technology investment costs

ψ^{tech} Supply technology investment costs

D Exogenous demand

l Lifetime of infrastructure

Variables

N Total consumption/production of all network technologies in a region

S Total consumption/production of all storage technologies in a region

T	Total consumption/production of all supply technologies in a region
x^{net}	Network technology activity
$x^{sto,in}$	Storage technology input activity
$x^{sto,level}$	Amount stored in storage technology
$x^{sto,out}$	Storage technology output activity
x^{tech}	Supply technology activity
Z	Cumulative discounted cost over the simulation horizon
Z^{fix}	Total fixed costs
Z^{inv}	Total investment costs
$z^{net,new}$	New network technology capacity
$z^{net,ret}$	Retired network technology capacity
z^{net}	Existing network technology capacity
$z^{sto,new}$	New storage technology capacity
$z^{sto,ret}$	Retired storage technology capacity
z^{sto}	Existing storage technology capacity
$z^{tech,new}$	New supply technology capacity
$z^{tech,ret}$	Retired supply technology capacity
z^{tech}	Existing supply technology capacity
Z^{tot}	Total annual cost
Z^{var}	Total variable costs

S1.1 Optimization model

Objective

The objective of the optimization is to identify the design (capacity) and activity variables of technology options included in the model that minimize the total discounted cost over the simulation horizon. The discounted cost is calculated as the annual cost of operation multiplied by the discount factor. The discount factor is weighted to reflect the multi-year decision-making (i.e., inter-temporal optimization across 5-year time steps). This yields the following objective function formulation:

$$\textbf{Min}\ \ Z = \sum_{y} \left(\delta_y \cdot Z_y^{tot} \right) \tag{1}$$

The model solves for the optimal variables subject to the constraints detailed below.

Resource balance with network flow and storage

To ensure demands are met, supply of each carrier within each region is constrained to be greater than the demand for the carrier in that region.

$$T_{r,c,y,m} + S_{r,c,y,m} + N_{r,c,y,m} \geq D_{r,c,y,m} \ \forall \ r, c, y, m \tag{2}$$

Carriers considered in the model are depicted in Figure (1) of the main text. Exogenous demands are defined for electricity, freshwater, and wastewater. Wastewater from the domestic and manufacturing sectors defined in this way are negative due to the contribution to resource availability.

Total consumption / production of carriers in each region by supply technologies is calculated with average conversion coefficients. These coefficients relate the activity of supply technologies to the consumption or production of a specific carrier (e.g., m^3 of water per kWh of electricity produced). Multiplying the activity of each technology by its activity ratio yields the total amount consumed or produced by a technology over the model period (1 month). These technology-level results are summed across the portfolio included to quantify the total transformation in each region:

$$T_{r,c,y,m} = \sum_{t,o} \epsilon^{tech}_{t,c,o} \cdot x^{tech}_{r,t,o,y,m} \;\forall\; r,c,y,m \tag{3}$$

We model electricity supply technologies across multiple operational modes to account for the effects of flexibility requirements, which are described in greater detail below.

A similar approach is used for storage technologies. Surface reservoirs and potable water storage at end-use are considered options for storing water between months. The need to track the storage level dynamically is addressed by breaking the storage activity into input and output components:

$$S_{r,c,y,m} = \sum_{s} \left(\epsilon^{sto,out}_{s,c} \cdot x^{sto,out}_{r,s,y,m} - \epsilon^{sto,in}_{s,c} \cdot x^{sto,in}_{r,s,y,m} \right) \;\forall\; r,c,y,m \tag{4}$$

Likewise, the total supply or consumption by network technologies are calculated by summing the total input and outputs across potential transmission pathways:

$$N_{r,c,y,m} = \sum_{rr,n} \left(\epsilon^{net,out}_{rr,r,c,n} \cdot x^{net}_{rr,r,n,y,m} - \epsilon^{net,in}_{r,rr,c,n} \cdot x^{net}_{r,rr,n,y,m} \right) \;\forall\; r,c,y,m \tag{5}$$

Network losses are incorporated in the framework, including energy use for water pumping with the procedure used to identify the network parameters detailed below.

For seasonal storage technologies, the level must also be balanced across time-periods. To ensure long-term sustainability of surface water reservoirs and prevent pre-filling of new storage investments (i.e., conservation of energy) we constrain the level at the end of the year to be equivalent to the initial value. These assumptions yield the following constraints:

$$x^{sto,level}_{r,s,y,m+1} = x^{sto,level}_{r,s,y,m} + x^{sto,in}_{r,s,y,m} - x^{sto,out}_{r,s,y,m} \;\forall\; r,s,y,m < m_f \tag{6}$$

$$x^{sto,level}_{r,s,y,m_f} + x^{sto,in}_{r,s,y,m_f} - x^{sto,out}_{r,s,y,m_f} = x^{sto,level}_{r,s,y,m_i} \;\forall\; r,s,y \tag{7}$$

Capacity adequacy

Operating flexibly impacts the efficiency and cost of power plants [1], and we distinguish between two operational modes for plants included to capture effects within the long-term modeling framework. The first mode represents steady or base-load operation, with the second mode representing flexible or load-following mode. Plants operating in load-following mode must be scheduled in advance, with the scheduled capacity required to move in both incremental and decremental directions to balance under and over forecast errors. This scheduling effect reduces the capacity available from power plants operating as a flexibility reserve. The scheduling impacts are emulated in the model by stipulating that power provided by power plants operating flexibly consumes twice the capacity as when it operates in base-load operation (i.e., capacity to move up or down is maintained in the flexible mode to account for scheduling). These assumptions yield the following capacity constraints for supply technologies:

$$\sum_{o} \left(\alpha_{t,o}^{tech} \cdot x_{r,t,o,y,m}^{tech} \right) \leq \phi_{r,t,m}^{tech} \cdot z_{r,t,y}^{tech} \; \forall \; r,t,y,m \tag{8}$$

$$\alpha_{t,o}^{tech} \cdot x_{r,t,o,y,m}^{tech} \leq \beta_{t,o}^{tech} \cdot \phi_{r,t,m}^{tech} \cdot z_{r,t,y}^{tech} \; \forall \; r,t,y,m \tag{9}$$

The load factor varies across months to reflect the variability of wind and solar generation. Water supply technologies are only considered to operate in a single operational mode with capacity usage assumed to scale one-to-one with activity.

To mitigate capacity constraints, new investments in capacity can be made in the model. Capacity retirements also accompany the decommissioning of ageing infrastructure. The capacity available in each year is therefore updated based on a balance of new investments and retirements:

$$z_{r,t,y+1}^{tech} = z_{r,t,y}^{tech} + z_{r,t,y}^{tech,new} + z_{r,t,y}^{tech,ret} \; \forall \; r,t,y < y_{end} \tag{10}$$

Forced retirements follow from a constraint on the lifetime of infrastructure:

$$z_{r,t,y+l_t}^{tech,ret} \geq z_{r,t,y}^{tech,new} \; \forall \; r,t,y < y_{end} - l_t \tag{11}$$

Similar capacity constraints are defined for storage:

$$x^{sto,level}_{r,s,y,m} \leq \phi^{sto}_{s} \cdot z^{sto}_{r,s,y} \; \forall \; r, s, y, m \tag{12}$$

$$z^{sto}_{r,s,y+1} = z^{sto}_{r,s,y} + z^{sto,new}_{r,s,y} + z^{sto,ret}_{r,s,y} \; \forall \; r, s, y < y_{end} \tag{13}$$

$$z^{sto,ret}_{r,s,y+l_s} \geq z^{sto,new}_{r,s,y} \; \forall \; r, t, y < y_{end} - l_s \tag{14}$$

For network technologies we reflect the bi-directional flow on possible pathways by constraining capacity in either direction to be equivalent and then divide the investment and operating costs equally between the pathways:

$$x^{net}_{r,rr,n,y,m} + x^{net}_{rr,r,n,y,m} \leq \phi^{net}_{n} \cdot z^{net}_{r,rr,n,y} \; \forall \; r, rr, n, y, m \tag{15}$$

$$z^{net}_{r,rr,n,y} = z^{net}_{rr,r,n,y} \; \forall \; r, rr, n, y \tag{16}$$

$$z^{net}_{r,rr,n,y+1} = z^{net}_{r,rr,n,y} + z^{net,new}_{r,rr,n,y} + z^{net,ret}_{r,rr,n,y} \; \forall \; r, rr, n, y < y_{end} \tag{17}$$

The current version of the model does not consider retirement of network technology or surface water reservoirs due to the selected simulation horizon (2050) and the long lifetimes typically associated with the infrastructure.

Minimum run requirements are included in the model to prevent fossil generation capacity contributing to reserve requirements without operating. We prescribed that the annual activity from power plants exceed 1% of installed capacity.

$$\sum_{o,m} x^{tech}_{r,t,o,y,m} \geq \mu \cdot z^{tech}_{r,t,y} \; \forall \; r, t, y \tag{18}$$

Cost accounting

Total costs of electricity and water system operation are calculated in each year by summing the investment, fixed and variable costs associated with each technology option:

$$Z^{tot}_{y} = Z^{inv}_{y} + Z^{fix}_{y} + Z^{var}_{y} \; \forall \; y \tag{19}$$

The investment costs are calculated based on the new capacity and no salvage value for retirements are currently considered.

$$Z_y^{inv} = \sum_{r,t} \left(\psi_{t,y}^{tech} \cdot z_{r,t,y}^{tech,new} \right) + \sum_{r,s} \left(\psi_{s,y}^{sto} \cdot z_{r,s,y}^{sto,new} \right) + \sum_{r,rr,y} \left(\psi_{n,r,rr,y}^{net} \cdot z_{r,rr,n,y}^{net,new} \right) \ \forall \ y \qquad (20)$$

Similarly, fixed costs are calculated based on existing capacity:

$$Z_y^{fix} = \sum_{r,t} \left(\gamma_{t,y}^{tech} \cdot z_{r,t,y}^{tech} \right) + \sum_{r,s} \left(\gamma_{s,y}^{sto} \cdot z_{r,s,y}^{sto} \right) + \sum_{r,rr,y} \left(\gamma_{n,y}^{net} \cdot z_{r,rr,n,y}^{net} \right) \ \forall \ y \qquad (21)$$

We only consider variable costs for supply technologies. Different costs are assumed for the operating modes to account for the cost of operating flexibly, and include fuel costs.

$$Z_y^{var} = \sum_{r,t,o,m} \left(\pi_{t,o,y}^{tech} \cdot x_{r,t,o,y,m}^{tech} \right) \ \forall \ y \qquad (22)$$

S1.2 Short-term electricity storage

Inter-temporal dispatch of short-term electricity storage is set exogenously, by defining a set number of recharge intervals per season and a minimum discharge time. Due to efficiency losses, the storage unit represents net seasonal energy consumption:

$$d = z \cdot \tau \cdot \left(\eta^2 - 1 \right) \cdot \xi \qquad (23)$$

where d is the total electricity consumption, z is the installed capacity, τ is the minimum storage discharge time, η is the one-way storage efficiency, and ξ is the number of recharge intervals per season.The operational strategy for a typical pumped storage technology used for short-term purposes described in [2] is used to parameterize the storage model.

S1.3 Energy for water conveyance

Energy requirements for water conveyance are parameterized after the analysis in [3]. The Darcy-Weisbach equation is used to estimate head losses due to turbulent flow in the pipeline:

$$h_f = f \cdot \frac{v^2}{2g} \cdot \frac{\Delta L}{D} \tag{24}$$

where h_f is the head loss due to friction, g is the acceleration due to gravity, f is the friction factor, ΔL is the pipe length, v is the average fluid velocity, and D is the inside pipe diameter. We utilize the parameters described in [3] to estimate an average energy input per km of horizontal conveyance. For vertical pumping we consider the energy needed to lift an equivalent volume of water:

$$p = \rho \cdot g \cdot \Delta h \cdot V \tag{25}$$

where ρ is the density of water, Δh is the elevation change and V is the volume of water.

Implementation

The optimization model is written in the GNU Mathematical Programming Language (GMPL) and solved with the CPLEX barrier method.

S2 Input data

S2.1 Electricity generation technologies

The electricity generation technologies included in the model are listed in Table (S1). The implemented cost and performance data for electricity generation are provided in Table (S2). Power generation costs and heat rates for 2010 are estimated from [2, 4]. Cost multipliers for the different power plant cooling technology costs are used to generate future projections (section S2.4). Cost and efficiency impacts of operating the unit flexibly are estimated from [1]. Water performance of the different power generation technologies are taken from [5]. Costs for the different power plant cooling technologies are distinguished following an analysis with a power plant cost model [6]. Load control technology costs are estimated from the supply curves in [7], with the capacity constrained to be less than 10% of the total electricity demand in each time period. Cost uncertainty for load control is included by considering the range in supply curves reported in [7] and a similar range in cost reductions are assumed for storage. Technology vintages and locations, as well as committed investments (future capacity installations) are estimated from [8–11] and are included in Table (S3).

Carbon emissions from fossil fuel combustion are tracked and constrained in the model. We use the Intergovernmental Panel on Climate Change's default values for crude oil (73.3 kg / GJ) and natural gas (56.1 kg / GJ) [12].

S2.2 Water supply technologies

The implemented cost and performance data for water supply technologies are provided in Table (S4). The water supply technologies included are reverse osmosis (RO) desalination, multi-stage flash (MSF) desalination, rainwater harvesting, groundwater withdrawals, and surface water withdrawals. Desalination energy costs are taken from [13], and for RO, include enhanced energy recovery. Costs for rainwater harvesting are estimated using the data reported for a multifamily unit in [14]. Average available rainfall in each region is then used to identify a monthly capacity factor. Wastewater treatment costs are estimated from [15]. The electricity intensity of rainwater harvestng systems is estimated from [16]. Investment and fixed costs for groundwater and surface water are excluded as it is assumed that most of this infrastructure is already in place and no further expansion is considered in

Energy Carrier	Fuel	Technology	Cooling System	Model Name
Urban Electricity	Natural Gas	Combined-cycle	Once-through - Freshwater	NGCC OT
			Once-through - Seawater	NGCC SW
			Closed-loop - Freshwater	NGCC CL
			Air-cooled	NGCC AC
		Single-cycle	Once-through - Freshwater	NGST OT
			Once-through - Seawater	NGST SW
			Closed-loop - Freshwater	NGST CL
			Air-cooled	NGST AC
		Combustion turbine	-	NGGT
	Oil	Combined-cycle	Once-through - Freshwater	OLCC OT
			Once-through - Seawater	OLCC SW
			Closed-loop - Freshwater	OLCC CL
			Air-cooled	OLCC AC
		Single-cycle	Once-through - Freshwater	OLST OT
			Once-through - Seawater	OLST SW
			Closed-loop - Freshwater	OLST CL
			Air-cooled	OLST AC
		Combustion turbine	-	OLGT
	Nuclear		Once-through - Freshwater	NC OT
			Once-through - Seawater	NC SW
			Closed-loop - Freshwater	NC CL
	Geothermal		Once-through - Freshwater	GEO OT
			Once-through - Seawater	GEO SW
	Solar	Concentrating w/o thermal storage	Once-through - Freshwater	CSP OT
			Once-through - Seawater	CSP SW
			Closed-loop - Freshwater	CSP CL
			Air-cooled	CSP AC
		Concentrating w/ thermal storage	Once-through - Freshwater	CSPTS OT
			Once-through - Seawater	CSPTS SW
			Closed-loop - Freshwater	CSPTS CL
			Air-cooled	CSPTS AC
		Photovoltaic	-	PV
	Wind	Onshore	-	WND
	-	Load Control	-	LC
		Short-term Electricity storage	-	ELS
Rural Electricity	Oil	Combustion Turbine	-	Rural OLGT
	Solar	Photovoltaic	-	Rural PV
	-	Short-term Electricity storage	-	Rural ELS

Table S1: Electricity supply technologies considered in the analysis.

Model name	Capital cost [$/kW]	Fixed cost [$/kW-yr]	Variable cost [$/MWh]	Flexible cost [$/MWh]	Baseload Heat rate [btu/kWh]	Flexible heat-rate [btu/kWh]	Load factor	ELCC	Water withdrawal [m^3/MWh]	Return flow [m^3/MWh]	Lifetime
NGCC OT	1023	15.37	3.27	2.17	6430	6816	0.85	0.9	39.8	39.3	30
NGCC CL	1064	15.98	3.40	2.17	6564	6958	0.85	0.9	0.7	0.1	30
NGCC AC	1105	16.60	3.53	2.17	6591	6986	0.85	0.9	-	-	30
NGCC SW	1023	15.37	3.27	2.17	6430	6816	0.85	0.9	-	-	30
NGGT	676	7.04	10.37	1.61	9750	10335	0.92	0.9	-	-	30
NGST OT	1159	16.18	3.27	2.05	10850	11501	0.85	0.9	132.8	131.2	30
NGST CL	1205	16.83	3.40	2.05	11033	11695	0.85	0.9	2.4	0.3	30
NGST AC	1251	17.47	3.53	2.05	12045	12767	0.85	0.9	-	-	30
NGST SW	1159	16.18	3.27	2.05	10850	11501	0.85	0.9	-	-	30
OLCC OT	1023	15.37	3.27	2.17	6430	6816	0.85	0.9	39.7	39.4	30
OLCC CL	1064	15.98	3.40	2.17	6564	6958	0.85	0.9	0.6	0.1	30
OLCC AC	1105	16.60	3.53	2.17	6591	6986	0.85	0.9	-	-	30
OLCC SW	1023	15.37	3.27	2.17	6430	6816	0.85	0.9	-	-	30
OLGT	676	7.04	10.37	1.61	9750	10335	0.92	0.9	-	-	30
OLST OT	1159	16.18	3.27	2.05	10850	11501	0.85	0.9	132.5	131.4	30
OLST CL	1205	16.83	3.40	2.05	11033	11695	0.85	0.9	2.1	0.4	30
OLST AC	1251	17.47	3.53	2.05	12045	12767	0.85	0.9	-	-	30
OLST SW	1159	16.18	3.27	2.05	10850	11501	0.85	0.9	-	-	30
NC OT	5530	93.28	2.14	2.05	-	-	0.90	0.9	176.6	175.0	30
NC CL	5751	97.01	2.23	2.05	-	-	0.90	0.9	5.7	1.2	30
NC SW	5530	93.28	2.14	2.05	-	-	0.90	0.9	-	-	30
GEO OT	6243	132.00	0.00	2.05	-	-	0.90	0.9	71.27	70.56	30
GEO SW	6243	132.00	0.00	2.05	-	-	0.90	0.9	-	-	30
CSP OT	5067	67.26	0.00	2.05	-	-	0.35	0.1	206.4	204.1	30
CSP CL	5270	69.95	0.00	2.05	-	-	0.34	0.1	3.5	3.4	30
CSP AC	5472	72.64	0.00	2.05	-	-	0.31	0.1	-	-	30
CSP SW	5067	67.26	0.00	2.05	-	-	0.35	0.1	-	-	30
CSPTS OT	7286	79.72	0.00	2.05	-	-	0.35	0.9	206.4	204.1	30
CSPTS CL	7577	82.90	0.00	2.05	-	-	0.31	0.9	3.5	3.4	30
CSPTS AC	7869	86.09	0.00	2.05	-	-	0.28	0.9	-	-	30
CSPTS SW	7286	79.72	0.00	2.05	-	-	0.35	0.9	-	-	30
PV	3873	24.69	0.00	0.00	-	-	0.35	0.1	-	-	30
WND	2213	39.55	0.00	0.00	-	-	0.35	0.1	-	-	30
LC	4000	0.01	0.00	0.00	-	-	0.90	0.9	-	-	20
ELS	3000	16.39	0.00	1.50	-	-	0.95	0.9	-	-	20
Rural OLGT	676	7.04	10.37	2.05	9750	10335	0.90	0.9	-	-	30
Rural PV	4183	27.75	0.00	0.00	-	-	0.35	0.9	-	-	30
Rural ELS	935	16.36	0.00	1.50	-	-	0.95	0.9	-	-	20

Table S2: Cost and performance of electricity supply technologies implemented in the model. Heat rates are used to convert fossil fuel generation output to fuel consumption and emissions. The water requirements for seawater cooled plants are not tracked as there is no constraint on seawater withdrawals beyond coastline accessibility. ELCC = effective load carrying capacity: the fraction of installed capacity allocated to peak load carrying capability of the system.

Province	Power Generation Capacity [MW] NGCC AC	NGCC SW	NGST SW	NGST AC	NGGT	OLCC AC	OLCC SW	OLST SW	OLST AC	OLGT	Rural OLGT
Asir	0	0	0	0	0	0	0	0	0	572	0
Bahah	0	0	0	0	0	0	0	0	0	0	0
N. Borders	0	0	0	0	0	0	0	0	0	629	45
Jawf	0	0	0	0	0	0	0	0	0	214	0
Madinah	0	0	0	0	0	0	0	0	0	202	0
Quassim	0	0	0	0	0	0	0	0	0	493	0
Riyad	1992	0	0	1151	721	0	0	0	0	1296	21
E. Region	0	520	6003	0	916	0	0	0	0	2010	0
Ha'il	0	0	0	0	0	0	0	0	0	210	0
Jizan	0	0	0	0	0	0	0	2400	0	618	20
Makkah	0	0	0	0	0	0	2983	8625	0	1134	0
Najran	0	0	0	0	0	0	0	0	0	289	61
Tabuk	0	0	0	0	0	0	0	0	0	902	70
Total	1992	520	6003	1151	1637	0	2983	11025	0	8568	216

Table S3: Estimated baseyear distribution of power generation in Saudi Arabia.

the model. Additional costs for surface and groundwater are accounted for by tracking the electricity used, which is assumed to be the primary component of supply costs.

The base-year distribution of unconventional water supply and wastewater treatment technologies in Saudi Arabia is provided in Table (S5), and are estimated from the analysis in [17]. The distribution of surface reservoirs and precipitation by month is provided in Table (S6) and is also estimated based on the analysis in [17].

Technology type	Capital cost [$\$/m^3$/day]	Fixed cost [$\$/m^3$/day]	Variable cost [$\$/m^3$]	Electricity Demand [kWh/m^3]	Heat Demand [MJ/m^3]	Lifetime
Groundwater	-	-	0.01	0.3 - 0.8	-	-
Surface water	-	-	0.01	0.1 - 0.3	-	-
Rainwater Harvesting (RWH)	590	15	0	0 - 0.2	-	30
Primary Wastewater Treatment (WWTP)	1000	0	0.04	0.3 - 0.5	-	30
Wastewater Recycling (WWTT)	1500	0	0.04	0.8 - 1	-	30
Multi-stage Flash Desalination (MSF)	1850	0	0.1	10 - 16	200 - 250	30
Reverse Osmosis Desalination (RO)	1700	0	0.1	3 - 5	-	30

Table S4: Cost and performance of water supply technologies implemented in the model. The range in reported energy intensities is used to parameterize a "min", "mean", and "max" water performance scenario. The "min" scenario is explored in the sensitivity analysis with the "mean" scenario used in the other cases.

S2.3 Electricity transmission and water conveyance

The electricity transmission and water conveyance data implemented in the mode is summarized in Tables (S7) and (S8). Electricity transmission capacity data is difficult to

Province	Water Supply Capacity [MCM/yr] MSF	RO	WWTP	Recycling
Asir	0	0	13	6
Bahah	0	0	0	0
N. Borders	0	0	0	0
Jawf	0	0	0	0
Madinah	117	39	59	28
Quassim	0	0	14	6
Riyad	0	0	267	128
E. Region	506	29	371	178
Ha'il	0	0	0	0
Jizan	1	0	0	0
Makkah	356	36	189	91
Najran	0	0	0	0
Tabuk	7	4	0	0
Total	986	108	913	438

Table S5: Estimated baseyear distribution of unconventional water supply and wastewater treatment technologies in Saudi Arabia. WWTP = Primary wastewater treatment (not suitable for potable reuse).

Province	Precipitation [mm/yr]	Surface Storage [MCM/yr]	Monthly Precipitation Fraction Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Asir	278	411	0.06	0.06	0.14	0.22	0.19	0.03	0.07	0.10	0.02	0.02	0.04	0.03
Bahah	81	41	0.10	0.06	0.16	0.30	0.15	0.02	0.02	0.05	0.01	0.02	0.04	0.06
N. Borders	96	21	0.22	0.09	0.17	0.17	0.02	0.02	0.00	0.00	0.00	0.07	0.08	0.16
Jawf	67	0	0.25	0.00	0.09	0.16	0.00	0.03	0.00	0.04	0.11	0.17	0.03	0.12
Madinah	202	85	0.16	0.02	0.17	0.24	0.09	0.01	0.00	0.01	0.00	0.02	0.19	0.08
Quassim	145	6	0.15	0.07	0.18	0.20	0.10	0.00	0.00	0.00	0.00	0.03	0.17	0.11
Riyad	93	92	0.13	0.11	0.26	0.25	0.03	0.00	0.00	0.00	0.00	0.01	0.07	0.14
E. Region	90	0	0.25	0.08	0.06	0.14	0.04	0.00	0.00	0.00	0.00	0.00	0.20	0.24
Ha'il	101	13	0.18	0.19	0.12	0.11	0.05	0.00	0.00	0.00	0.05	0.09	0.13	0.08
Jizan	202	246	0.06	0.02	0.04	0.09	0.08	0.06	0.11	0.16	0.11	0.11	0.07	0.06
Makkah	202	336	0.19	0.01	0.06	0.11	0.01	0.00	0.01	0.05	0.05	0.13	0.20	0.19
Najran	22	90	0.00	0.43	0.02	0.05	0.17	0.15	0.00	0.07	0.00	0.11	0.00	0.00
Tabuk	120	7	0.15	0.24	0.13	0.09	0.05	0.00	0.00	0.00	0.05	0.07	0.11	0.12

Table S6: Precipitation and surface water storage data implemented in the modeling framework.

obtain and we alternatively estimated existing and planned capacities between regions based on maps provided by the regional balancing area authority [18, 19]. Water conveyance capacity between regions is estimated from recent regional assessments [17, 20]. Transmission costs are taken from another electricity planning model with a similar representation [21], while water conveyance infrastructure costs are estimated from a recent analysis for Saudi Arabia [22]. No cost improvements for network technologies are considered in the model. Existing interprovincial water conveyance is estimated from [17], and includes a 360 MCM/yr connection between E. Region and Riyad, a 20 MCM/yr connection between E. Region and Qassim, and a 10 MCM/yr line between Makkah and Asir.

Network Technology	Capacity units	Capital cost [$/capacity-km]	Fixed O&M [$/capacity-yr]	Lifetime	Efficiency loss [%/km]
Electricity Transmission	kW	1.13	0.01	60	0.006
Freshwater Transfer	m^3/day	6.70	0.03	60	0.03

Table S7: Estimated costs for network technologies.

S2.4 Cost projections and sensitivity

The long-term cost projections implemented in the model are provided in Table (S9). An investment cost multplier is used to shift the base-year investment costs in future model years to reflect anticpated long-term improvements and uncertainties. Future cost changes for electricity generation technology are estimated from the recent projections released by the National Renewable Energy Labratory [23]. We specifically consider the min, mean, and max range projected in the NREL data to generate the cost multipliers. These multipliers are then applied to the costs listed in Table (S2). For water supply technologies, moderate cost improvements are anticipated [13], and we alternatively vary the base-year captial costs according to the uncertainty ranges reported in [13–15, 20].

S2.5 Resource potentials

Renewable energy potentials are derived for each province by defining an average monthly capacity factor (the fraction of total installed capacity that can be produced annually) for each technology. For solar energy, intra-annual geographic diversity is modeled using monthly observations of solar intensity from a number of measurement stations [19]. These data are

Province Start	Province End	Distance [km]	Elevation Δ [m]	Line Rating	Est. Capacity [MW]	Status
Asir	Riyad	954	-1788	1 X 380 kV	467	E
Asir	Jizan	200	-2360	2 X 380 kV	934	E
Asir	Makkah	600	-2123	1 X 380 kV	467	P
Asir	Najran	249	-1107	1 X 380 kV	467	E
Bahah	Makkah	311	-1878	1 X 380 kV	467	E
N. Borders	Jawf	163	30	1 X 380 kV	467	P
N. Borders	E. Region	966	-526	1 X 380 kV	467	E
Jawf	Ha'il	391	426	1 X 380 kV	467	E
Jawf	Makkah	467	194	1 X 380 kV	467	P
Madinah	Quassim	509	40	1 X 380 kV	467	E
Madinah	Ha'il	481	384	1 X 380 kV	467	P
Madinah	Makkah	441	-331	2 X 380 kV	934	E
Madinah	Tabuk	620	152	2 X 380 kV	934	E
Quassim	Riyad	359	-36	3 X 380 kV	1401	E
Quassim	E. Region	720	-638	1 X 380 kV	467	E
Quassim	Ha'il	269	344	1 X 380 kV	467	E
Riyad	E. Region	478	-602	4 X 380 kV	1868	E
Riyad	Makkah	876	-335	1 X 380 kV	467	P
Jizan	Makkah	702	237	1 X 380 kV	467	E
Jizan	Najran	328	1253	1 X 380 kV	467	E

Table S8: Estimated baseyear distribution of electricity transmission technologies [18, 19]. Line ratings were converted to estimated transfer capabilities based on the historical transfer capabilities between zones described in [8]. Existing lines (status = E) are assumed to already be available in the baseyear, whereas planned lines (status = P) are assumed available in 2015.

Technology	Scenario	2010	2015	2020	2025	2030	2035	2040	2045	2050
PV	min	1.00	0.50	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	mid	1.00	0.52	0.43	0.36	0.29	0.29	0.29	0.29	0.29
	max	1.00	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
WND	min	1.00	0.71	0.67	0.65	0.63	0.63	0.63	0.63	0.63
	mid	1.00	0.78	0.76	0.74	0.74	0.73	0.73	0.73	0.73
	max	1.00	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
CSPTS	min	1.00	0.93	0.42	0.42	0.42	0.42	0.42	0.42	0.42
	mid	1.00	0.93	0.56	0.49	0.42	0.42	0.42	0.42	0.42
	max	1.00	0.93	0.70	0.70	0.70	0.70	0.70	0.70	0.70
CSP	min	1.00	0.93	0.42	0.42	0.42	0.42	0.42	0.42	0.42
	mid	1.00	0.93	0.56	0.49	0.42	0.42	0.42	0.42	0.42
	max	1.00	0.93	0.70	0.70	0.70	0.70	0.70	0.70	0.70
NGCC / OLCC	min	1.00	0.99	0.93	0.91	0.89	0.88	0.87	0.87	0.87
	mid	1.00	0.99	0.93	0.91	0.89	0.88	0.87	0.87	0.87
	max	1.00	0.99	0.93	0.91	0.89	0.88	0.87	0.87	0.87
NGGT / OLGT	min	1.00	0.92	0.89	0.87	0.85	0.83	0.83	0.83	0.83
	mid	1.00	0.92	0.89	0.87	0.85	0.83	0.83	0.83	0.83
	max	1.00	0.92	0.89	0.87	0.85	0.83	0.83	0.83	0.83
NC	min	1.00	0.97	0.85	0.83	0.80	0.78	0.76	0.76	0.76
	mid	1.00	0.97	0.85	0.83	0.80	0.78	0.76	0.76	0.76
	max	1.00	0.97	0.85	0.83	0.80	0.78	0.76	0.76	0.76
LC / ELS	min	1.00	1.00	0.50	0.33	0.33	0.33	0.33	0.33	0.33
	mid	1.00	1.00	0.67	0.50	0.33	0.33	0.33	0.33	0.33
	max	1.00	1.00	0.92	0.83	0.67	0.67	0.67	0.67	0.67
MSF	min	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	mid	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	max	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
RO	min	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
	mid	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	max	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47
RWH	min	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	mid	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	max	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
WWTT	min	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	mid	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	max	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30

Table S9: Investment cost multipliers for supply technologies.

then calibrated to reflect the anticipated performance of actual solar power systems (average capacity factor of 30%) estimated from a detailed technological assessment [24]. For wind energy, many of the best sites lie on the Western coast [19, 25], and we constrain wind expansion to these provinces and assume an average capacity factor of 30%. Similarly, we constrain geothermal expansion to provinces with known geothermal potential [26].

Without connection to a hydrological model tracking surface water availability, the provincial distribution of surface water resources is assumed to follow the distribution of reservoir capacities [17]. We then model the monthly contribution of annual run-off following the historical spatial monthly precipitation distribution. Access to seawater is constrained to provinces with coastlines. For rainwater harvesting, the historical average precipitation is used to identify a monthly capacity factor in each region.

S3 Demand scenarios

S3.1 Reference scenario

Demands for electricity and water occurring in the agricultural, domestic, and manufacturing sectors drive capacity expansion requirements and thus represent crucial model inputs. Econometric models are widely used to generate demand projections, and we apply a similar approach to generate demands for Saudi Arabia. We identify semi-logarithmic models between historical per capita GDP and domestic sector electricity and water withdrawal to reflect saturation of useful services with increasing income-level [27, 28]. Historical energy consumption data is obtained from the International Energy Agency [29], historical water data is obtained from the United Nations Food & Agricultural Organization [30], and historical socioeconomic indicators are obtained from the World Bank [31]. Least squares analysis is then used with these data to identify the models included in Table (S10). Urban and rural income inequalities are estimated by downscaling national GDP following the procedure described in Grübler et al. [32]. Manufacturing demands are estimated with a similar model that treats downscaled provincial GDP as the independent variable, with electricity used for desalination subtracted from the baseyear data using the estimated capacity and energy intensity in 2010. Wastewater (return-flow) from the manufacturing and domestic sectors is estimated based on national consumption efficiencies taken from a recent global analysis [28].

Agricultural demand projections account for the additional relationship observed between irrigation water requirements and national agricultural policy. Historically, cereals were promoted and grown as an export crop, but due to irrigation requirements and the impact on groundwater, Saudi Arabia's agricultural policy recently moved towards phasing out this water intensive crop and in the direction of producing higher value fruits and vegetables for local consumption [33]. It can be expected that as income-levels increase in Saudi Arabia, the demand for higher value food products will as well [34], potentially leading to higher irrigation withdrawals to support cultivation locally. We reflect these anticipated income effects on agricultural water use by first removing the volume applied for cereals from the historical data based on a recent analysis of irrigation water demands [33], and then fitting a semi-logarithmic model between the remaining agricultural water demand and per capita

GDP. Irrigation for cereal crops is assumed to stagnate post-2010. The majority of water withdrawn for irrigation is consumed, and for this reason we exclude return-flow from the agricultural sector. For agricultural electricity demand, we find no clear relationship with historical irrigation volumes and alternatively utilize the estimated baseyear agricultural water-energy intensity (kWh/m^3) for future projections.

For the demand projections, we utilize population, urbanization, and GDP projections aligned with the shared socioeconomic pathways (SSP) [35–38]; the most recent socioeconomic scenarios put forward by the international global change research community. We specifically focus on the SSP2 scenario, a mid-range 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 [36, 38].

We utilize the quantitative scenario data to generate a single national-level electricity and freshwater demand trajectory for each sector out to 2050, with the aggregated results depicted in Figure (S5). Moderate levels of end-use technological change are included (1 % per year compound annual reduction), and reflect expected efficiency improvements driven by technological innovation. Positive growth coefficients are stipulated for electricity (1 % per year compound annual increase) due to the anticipated growth in electrified end-uses (e.g., air conditioning and electric vehicles). It is important to note that the resulting electricity demand trajectory is somewhat conservative to other recent projections [39]. The estimated national domestic and industrial demands are downscaled to the provincial level based on the population distribution, whereas agricultural demands are disaggregated following the historical distribution [30]. Monthly domestic electricity demands are decomposed based on historical trends [39]. Domestic and irrigation water demands are broken into monthly components based on the estimated moisture deficit, calculated across 1/4 degree grid cells and weighted based on population for domestic demands [40]. The distribution across each region is summarized in Table (S11).

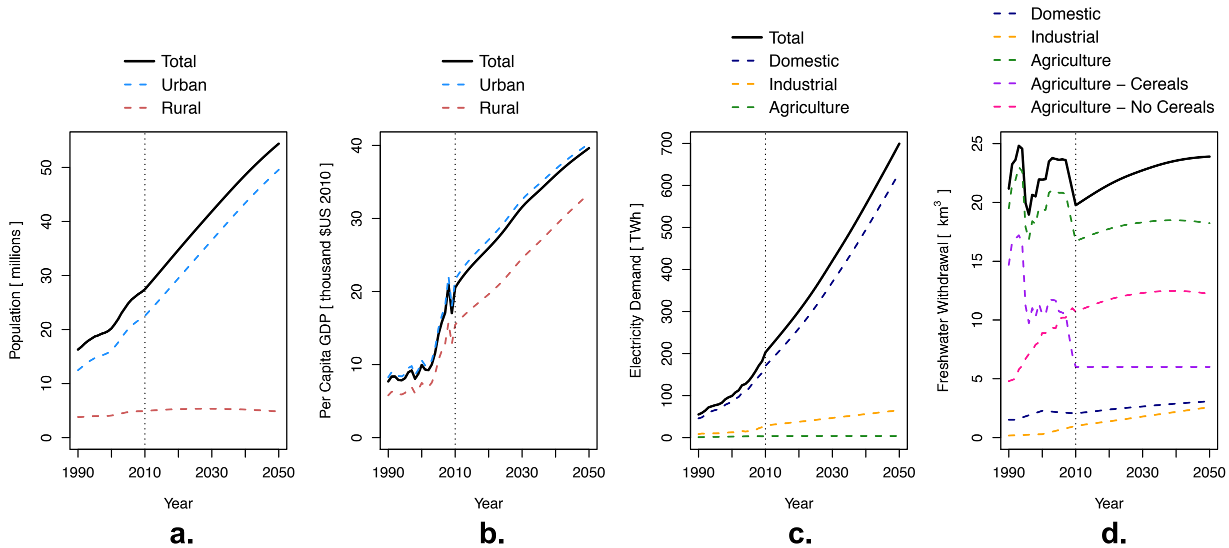


Figure S1: National socioeconomic and demand projections for the SSP2 scenario. a. Population; b. Per capita GDP; c. Electricity demand; and d. Freshwater withdrawal. Industrial demands exclude electricity for desalination and cooling water for thermoelectric generation.

Sector	Resource	Demand Equation	Units	Model Parameters		
				a	b	λ
Domestic	Freshwater	$(a + b \cdot \ln g) \cdot \phi \cdot \lambda^y$	m^3/capita	356.96	-28.71	1.00
	Electricity	$(a + b \cdot \ln g) \cdot \phi \cdot \lambda^y$	kWh/capita	-15745.75	2194.47	1.01
Industrial	Freshwater	$(a + b \cdot \ln G) \cdot \phi \cdot \lambda^y$	km^3	-12.89	0.51	0.99
	Electricity	$(a + b \cdot \ln G) \cdot \phi \cdot \lambda^y$	km^3	-222.15	9.04	0.99
Agriculture	Freshwater	$(a + b \cdot \ln g) \cdot \phi \cdot \lambda^y$	m^3/capita	692.73	-29.16	0.99
	Electricity	$a \cdot \lambda^y$	kWh/m^3	0.22	-	0.99

Table S10: Identified demand models for the domestic, industrial, and agricultural sectors. The parameter ϕ represents the base-year model error, and decays to unity along an exponential trajectory to represent convergence over time. Agriculture water requirements exclude irrigation for cereal crops, which is assumed to stagnate over future periods. G = GDP, and g = per capita GDP. Positive technological change parameters λ are stipulated for electricity due to the anticipated growth in electrified end-uses (e.g., air conditioning and electric vehicles) that may outpace autonomous efficiency improvements. Least-squares analysis is applied to identify model coefficients with data from IEA [29], FAO [30], and the World Bank[31].

		Monthly Demand Fraction											
Province	% Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Asir	1.9	0.075	0.077	0.079	0.086	0.089	0.096	0.09	0.087	0.089	0.084	0.075	0.074
Bahah	0.2	0.077	0.078	0.078	0.085	0.089	0.095	0.091	0.087	0.087	0.084	0.076	0.073
N. Borders	0.0	0.065	0.072	0.075	0.083	0.093	0.101	0.102	0.099	0.092	0.082	0.069	0.066
Jawf	8.8	0.067	0.071	0.076	0.083	0.093	0.101	0.101	0.099	0.092	0.081	0.069	0.066
Madinah	2.4	0.070	0.075	0.081	0.087	0.092	0.097	0.094	0.091	0.090	0.082	0.072	0.070
Quassim	18.8	0.068	0.073	0.078	0.088	0.092	0.097	0.097	0.093	0.091	0.083	0.071	0.069
Riyad	24.0	0.070	0.074	0.077	0.085	0.091	0.097	0.096	0.092	0.090	0.084	0.073	0.070
E. Region	9.2	0.071	0.075	0.078	0.086	0.092	0.097	0.094	0.091	0.089	0.083	0.074	0.070
Ha'il	10.8	0.068	0.072	0.077	0.086	0.093	0.099	0.098	0.096	0.091	0.082	0.071	0.067
Jizan	15.1	0.074	0.079	0.080	0.087	0.088	0.096	0.089	0.088	0.089	0.083	0.075	0.074
Makkah	3.8	0.073	0.077	0.081	0.086	0.090	0.095	0.091	0.088	0.090	0.083	0.074	0.073
Najran	1.1	0.073	0.077	0.080	0.086	0.089	0.097	0.089	0.088	0.088	0.083	0.075	0.073
Tabuk	4.0	0.069	0.073	0.077	0.086	0.092	0.099	0.098	0.095	0.090	0.081	0.071	0.068

Table S11: Regional and monthly breakdown of irrigation requirements. Regional distribution is taken from FAO [30]. The percent total is used to disaggregate the national agricultural sector electricity and water demand projections to the provincial level, and is held constant over future periods. The monthly distribution is assumed to follow the moisture deficit, which is calculated across 1/4 degree grid cells and averaged across regions following the procedure described in [40].

S3.2 Sensitivity scenarios

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 behaviour. The alternative scenarios are generated by varying the technological change parameter λ in Table 10 such that the demands decrease by 40% in the year 2050 relative to the reference scenario. This represents a potential for water and electricity conservation similar to that identified in recent analyses [41, 42]. 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. Finally, we combine all conservation measures to generate an *Optimistic* development scenario. The alternative demand scenarios are depicted in Figures 2 to 5 below.

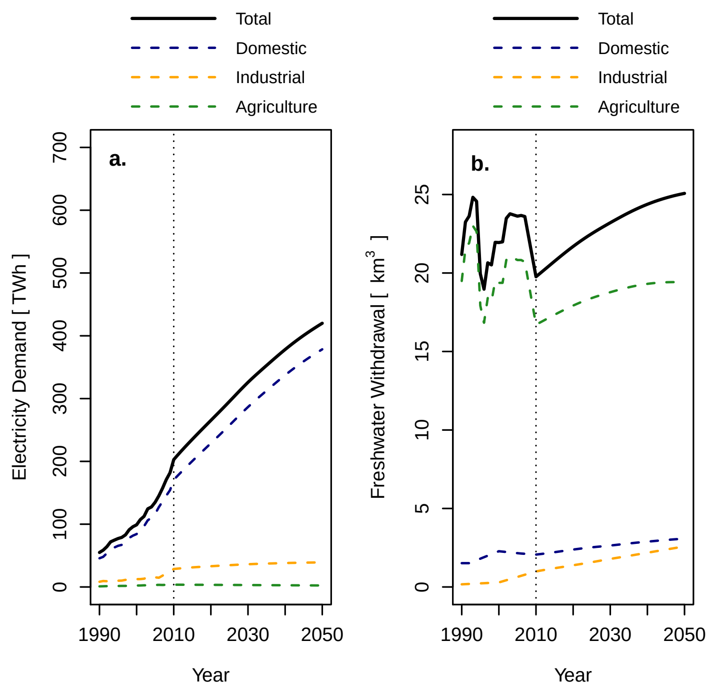


Figure S2: Demand projections for the "Electricity conservation" scenario. a. Electricity demand; and b. Freshwater withdrawal.

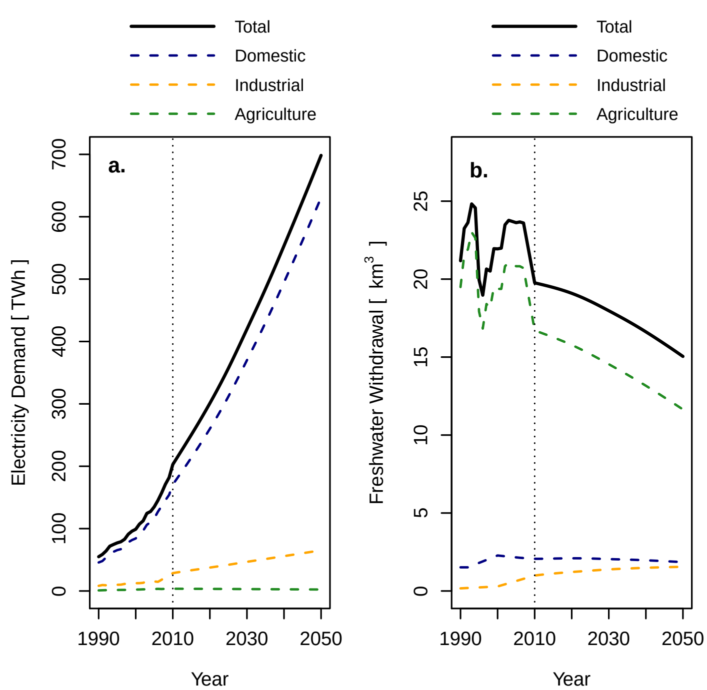


Figure S3: Demand projections for the "Water conservation" scenario. a. Electricity demand; and b. Freshwater withdrawal.

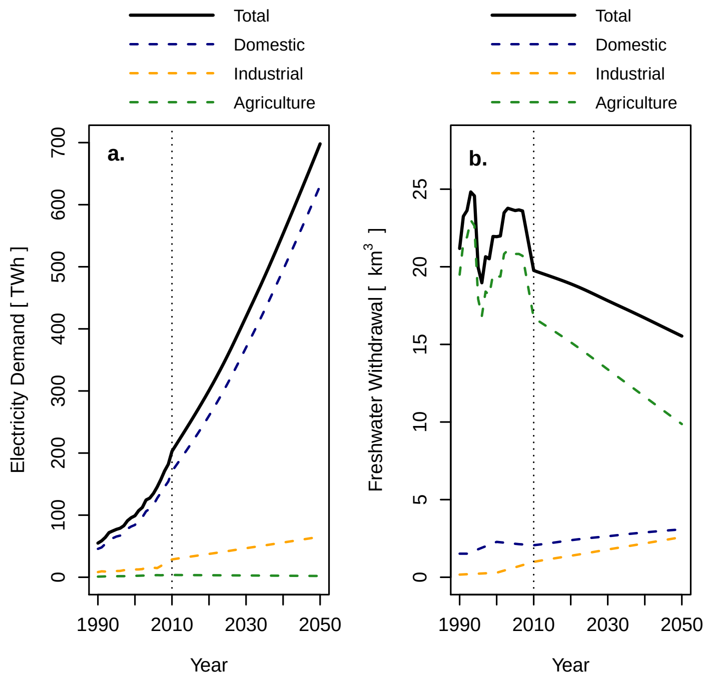


Figure S4: Demand projections for the "Increased food imports" scenario. a. Electricity demand; and b. Freshwater withdrawal.

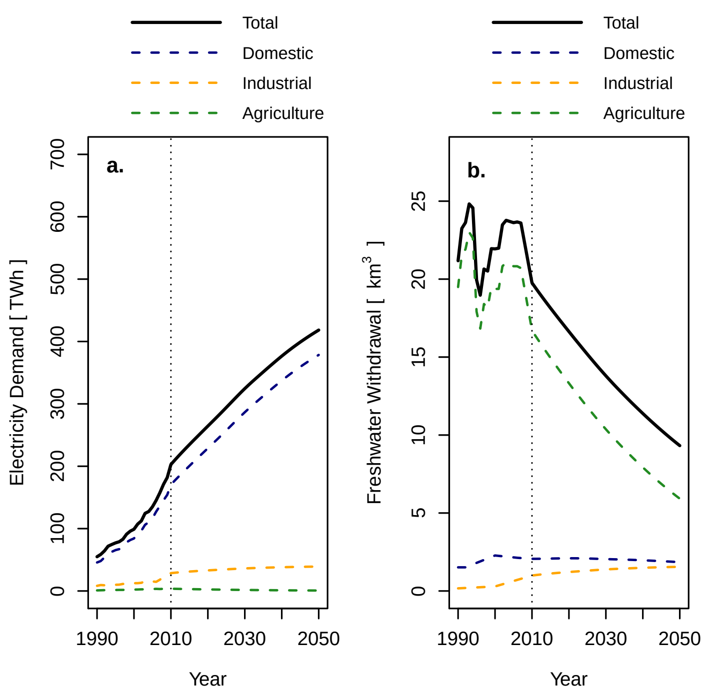


Figure S5: Demand projections for the "Optimistic" scenario. a. Electricity demand; and b. Freshwater withdrawal.

S4 Supplementary results

S4.1 Provincial delineation

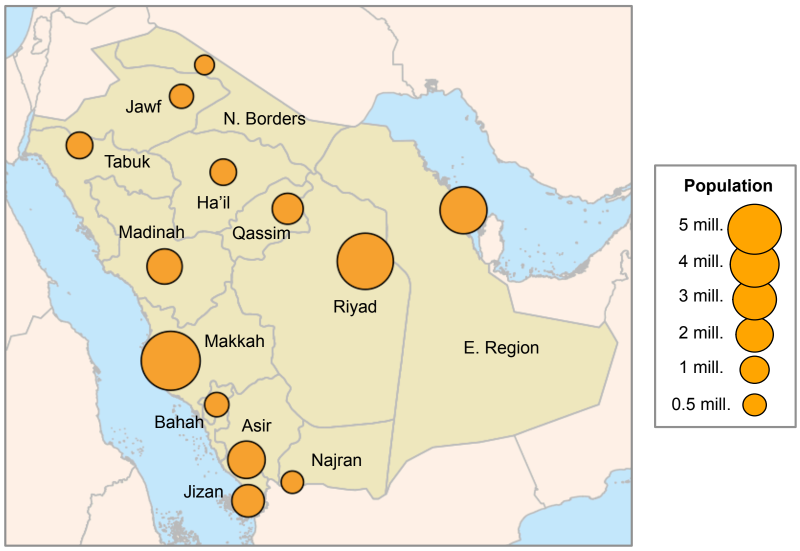


Figure S6: Spatial extent of subnational regions considered in the model align with provincial administrative boundaries. The locations of provincial capital cities are used to estimated network parameters, and are depicted along with the estimated 2010 provincial population distribution.

S4.2 Provincial technology distributions in 2050

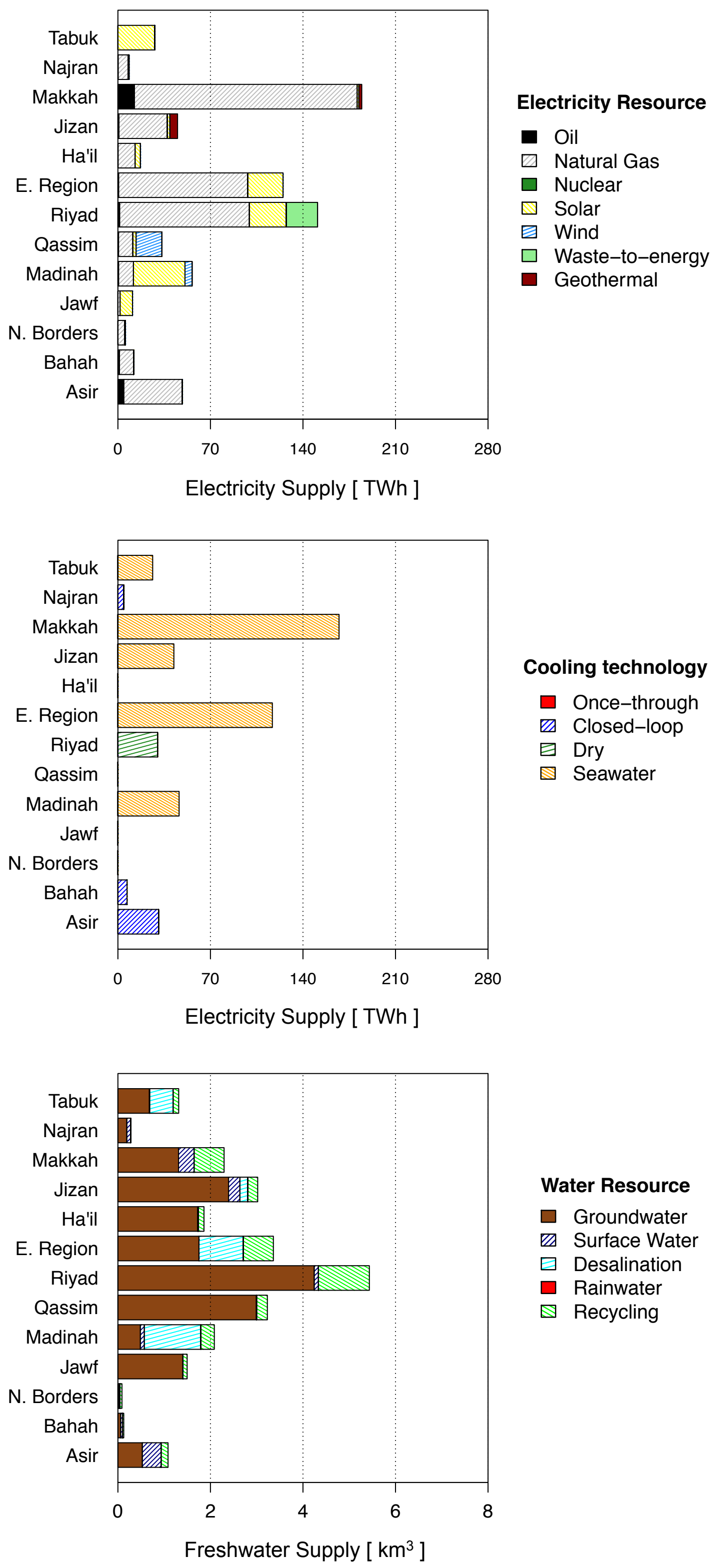


Figure S7: **0% reduction in groundwater withdrawals, and 0% reduction in cumulative CO2 emissions**. Optimal supply technology distributions in 2050. Top: electricity supply by resource. Middle: electricity supply by cooling technology. Bottom: water supply by source.

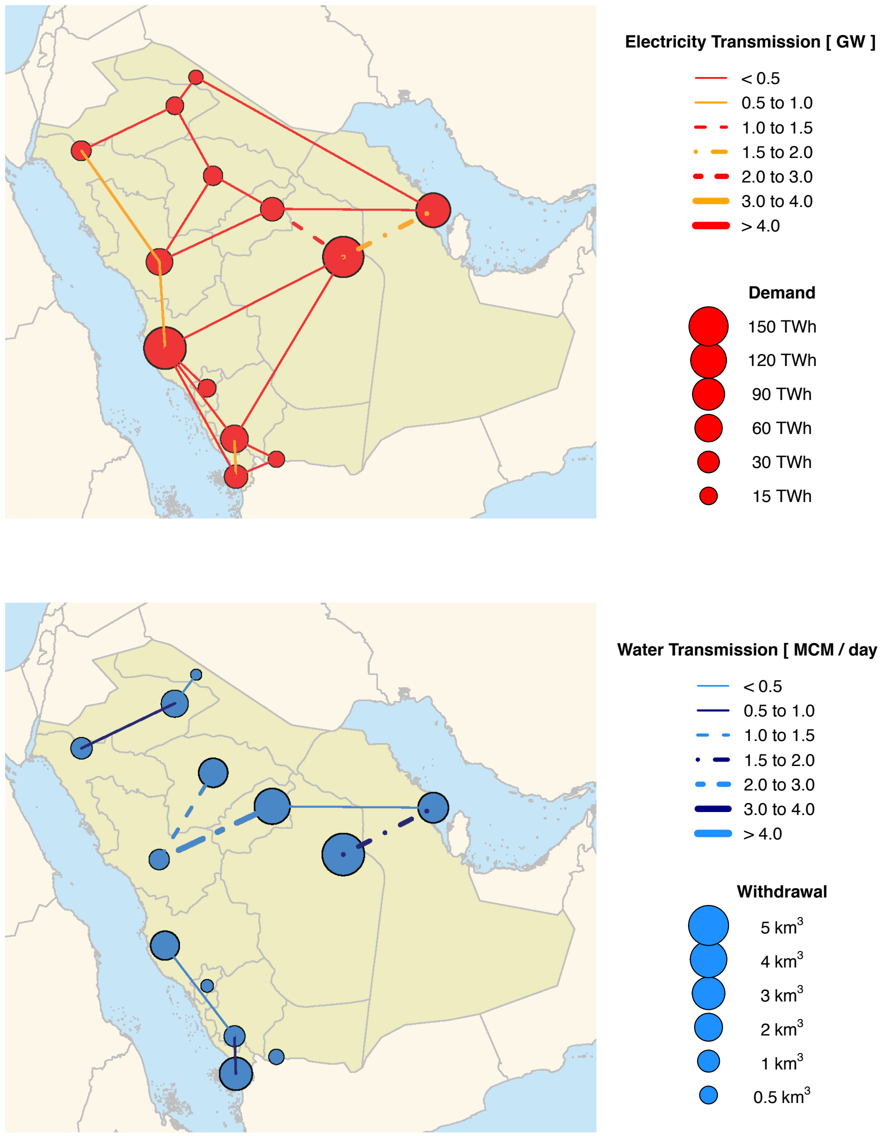


Figure S8: **0% reduction in groundwater withdrawals, and 0% reduction in cumulative CO2 emissions**. Optimal network technology distributions in 2050. Top: interprovincial electricity network. Bottom: interprovincial freshwater network.

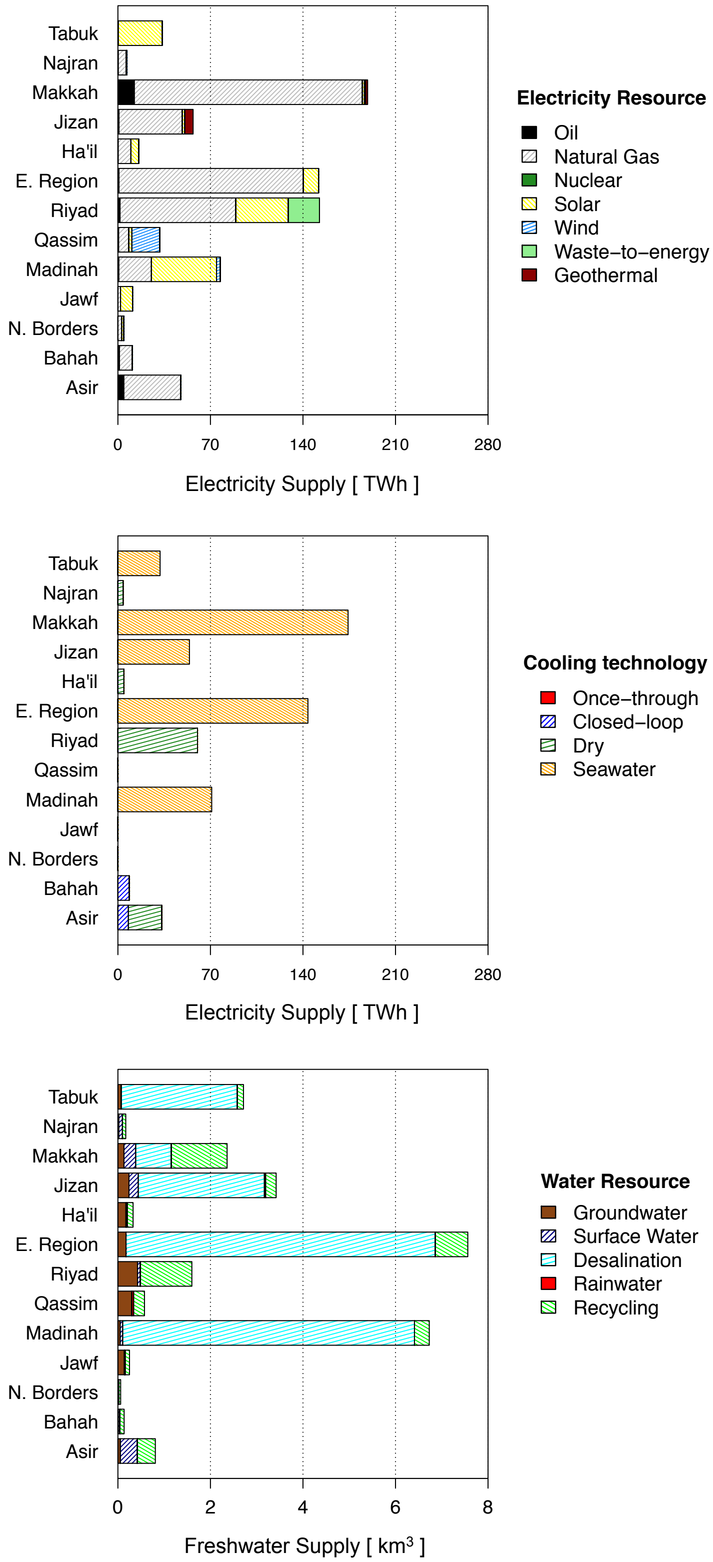


Figure S9: **90% reduction in groundwater withdrawals, and 0% reduction in cumulative CO2 emissions**. Optimal supply technology distributions in 2050. Top: electricity supply by resource. Middle: electricity supply by cooling technology. Bottom: water supply by source.

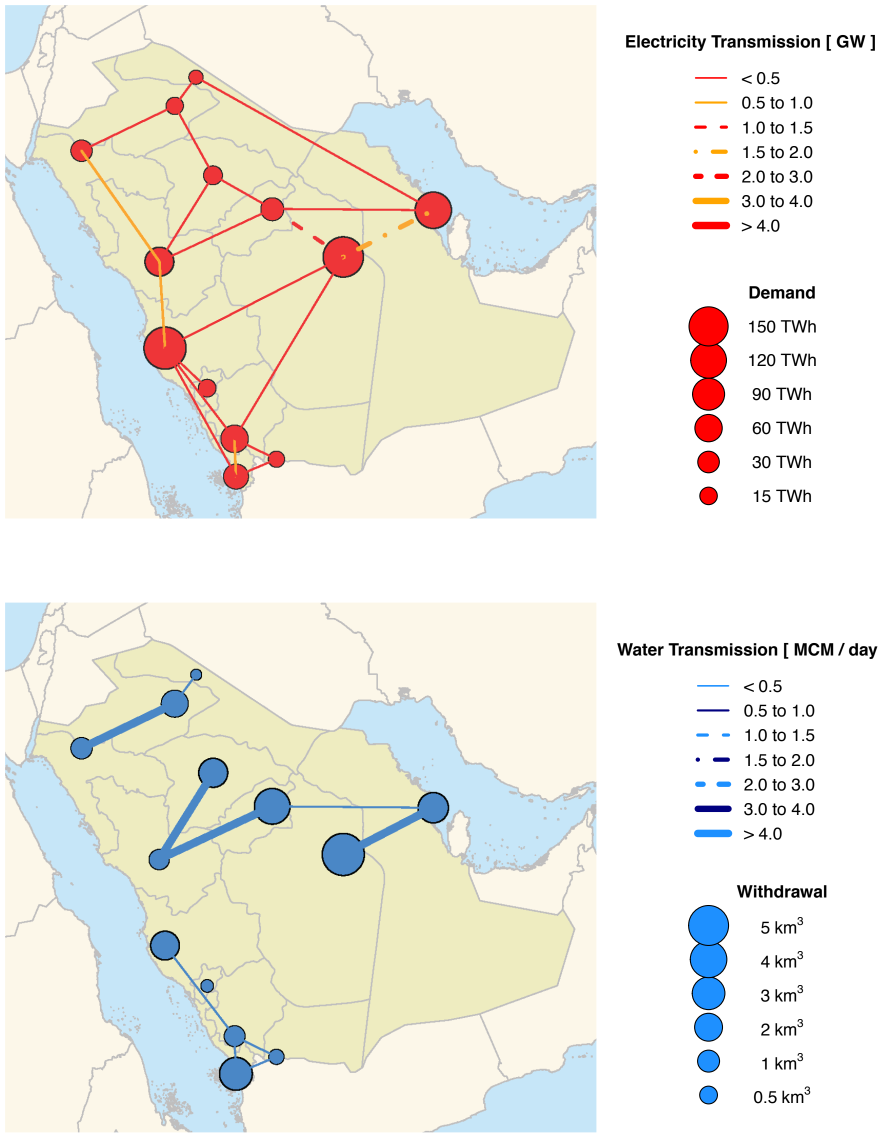


Figure S10: **90% reduction in groundwater withdrawals, and 0% reduction in cumulative CO2 emissions**. Optimal network technology distributions in 2050. Top: interprovincial electricity network. Bottom: interprovincial freshwater network.

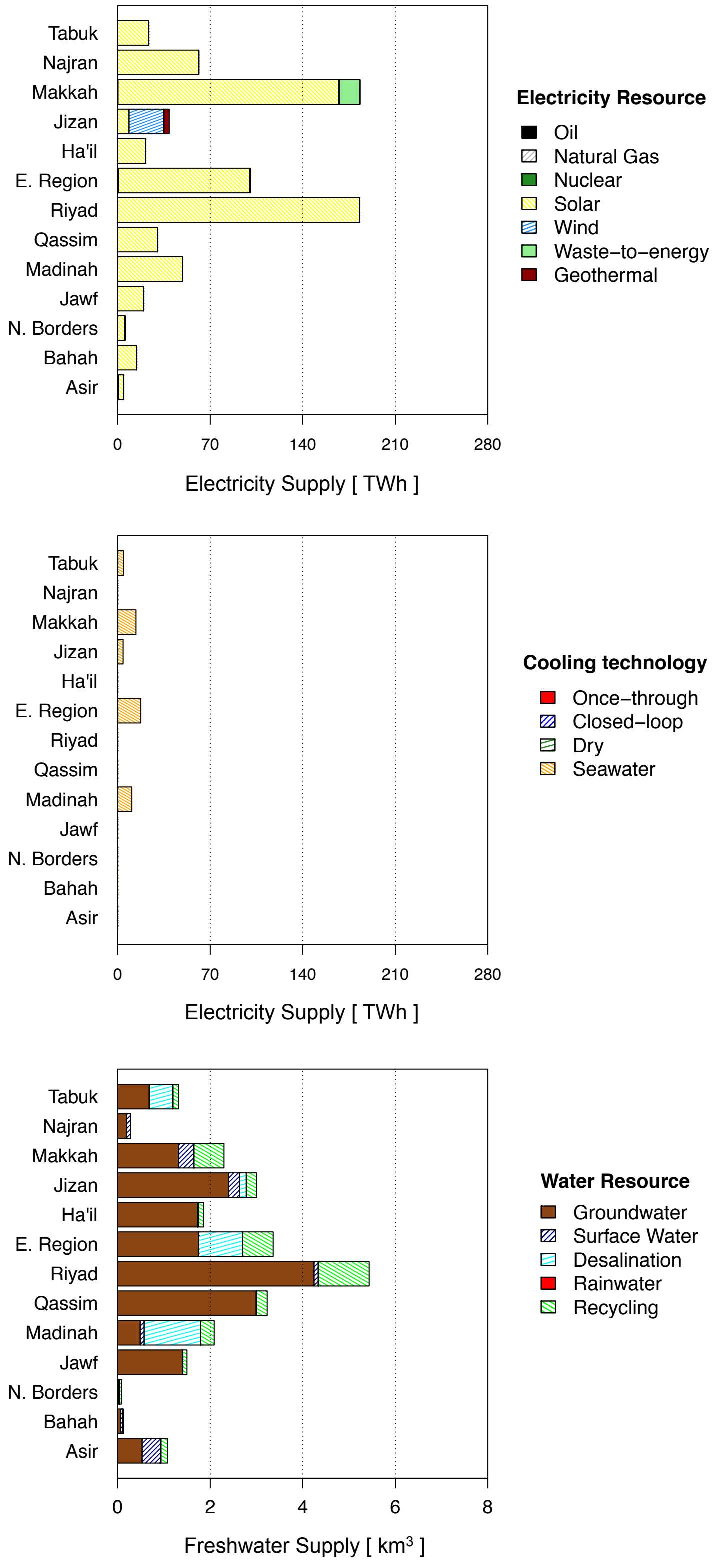


Figure S11: **0% reduction in groundwater withdrawals, and 80% reduction in cumulative CO2 emissions**. Optimal supply technology distributions in 2050. Top: electricity supply by resource. Middle: electricity supply by cooling technology. Bottom: water supply by source.

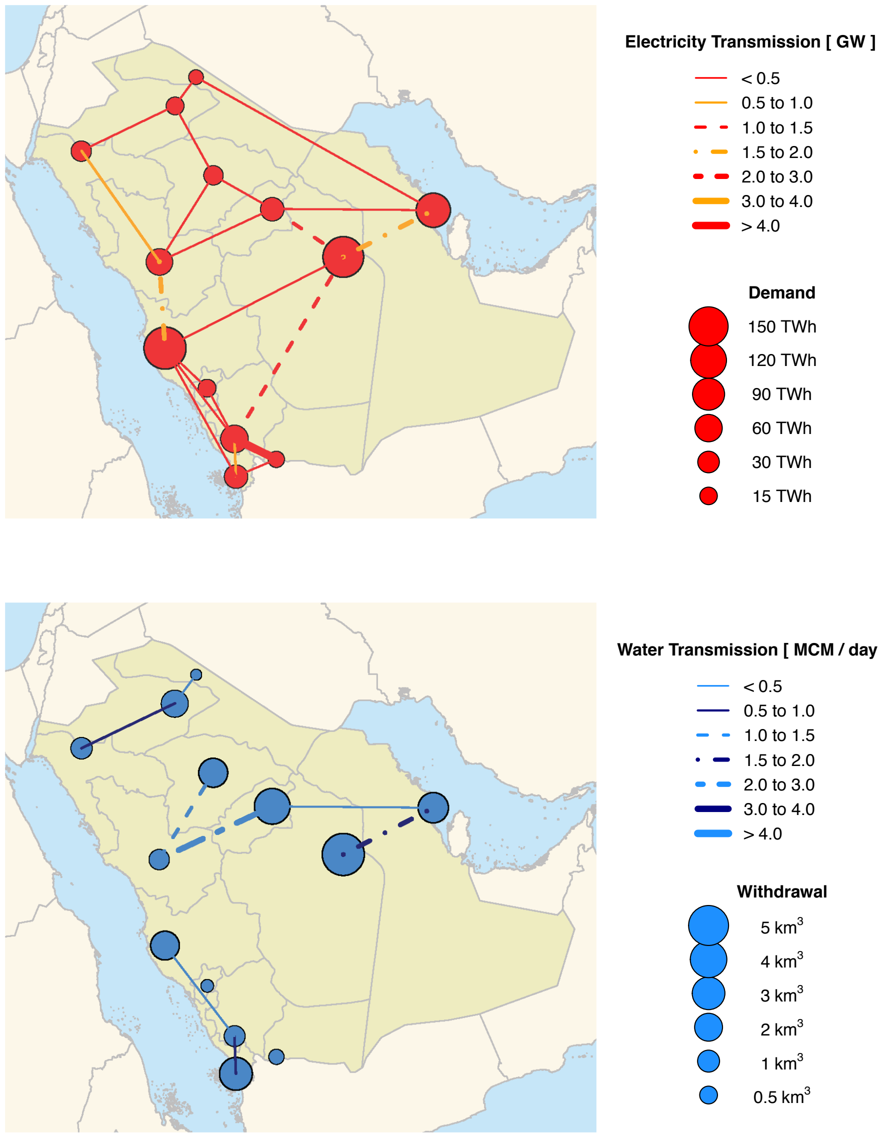


Figure S12: **0% reduction in groundwater withdrawals, and 80% reduction in cumulative CO2 emissions**. Optimal network technology distributions in 2050. Top: interprovincial electricity network. Bottom: interprovincial freshwater network.

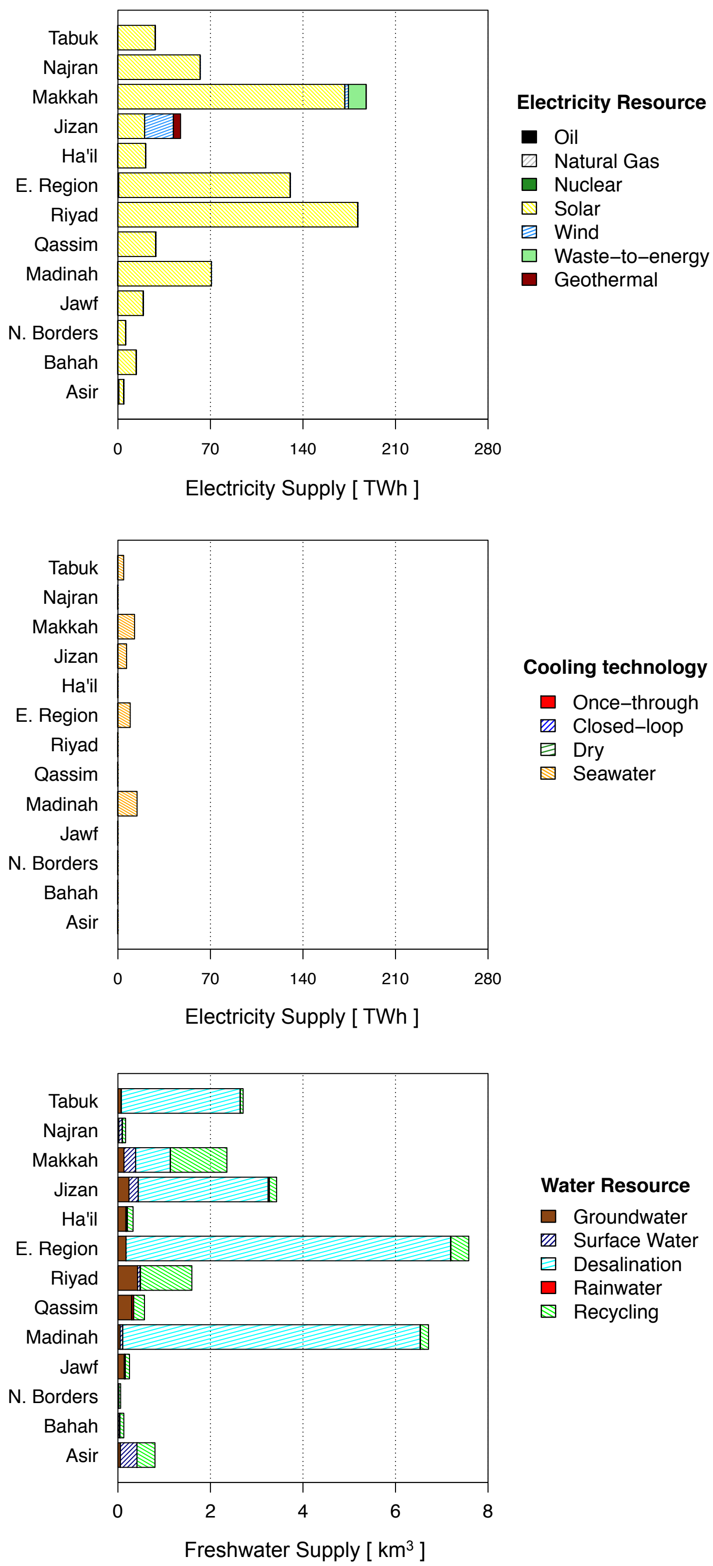
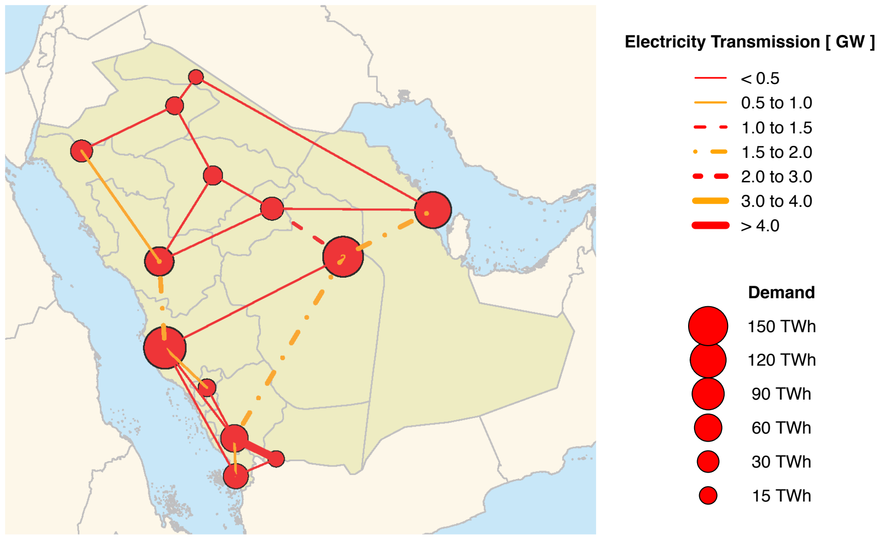


Figure S13: **90% reduction in groundwater withdrawals, and 80% reduction in cumulative CO2 emissions**. Optimal supply technology distributions in 2050. Top: electricity supply by resource. Middle: electricity supply by cooling technology. Bottom: water supply by source.



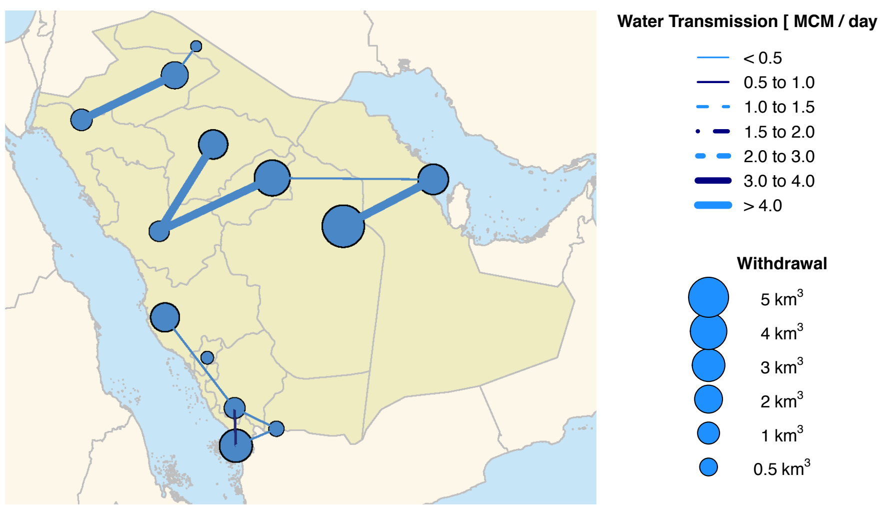


Figure S14: **90% reduction in groundwater withdrawals, and 80% reduction in cumulative CO2 emissions**. Optimal network technology distributions in 2050. Top: interprovincial electricity network. Bottom: interprovincial freshwater network.

References

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