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A metropolitan scale analysis of the impacts of future electricity mix alternatives on the water-energy nexus

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HIGHLIGHTS

- Future water-energy interactions are modeled in the Phoenix Metropolitan region.
- Fast transition to renewable energy will save water and reduce CO_2 emissions.
- Intense droughts will slightly reduce energy used by water infrastructure.
- Costs of renewable and business as usual scenarios are comparable.

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ABSTRACT

Current population and climate trends are increasing the need to adopt holistic approaches for managing water and energy systems, especially in water-limited regions like the Southwestern U.S. In this study, we quantify the implications of future energy mix alternatives on the water-energy nexus in the Phoenix, Arizona metropolitan region using the Long-range Energy Alternatives Planning (LEAP) platform. We first show that LEAP is able to simulate historical observations of energy generation and consumption from 2001 to 2018. We then simulate future electricity generation through 2060 under the same demand projections and different energy mix solutions. Results of our simulations are as follows. (i) Water heating accounts for 71% of the total water-related uses and its energy needs are projected to double in 2060, due to population growth; the energy required to treat and move water is instead expected to decrease by 9%, mainly because of declining agricultural water demands. (ii) Energy mix solutions that transition faster to renewable sources are more sustainable than a business as usual scenario that relies more on fossil fuels, because renewable technologies require less water for electricity generation (−35%) and reduce CO_2 emissions (−57%). (iii) The aggressive transition to renewable energy is projected to have higher structural costs than the business as usual scenario, but comparable total expenses because of the lower operational cost of renewable technologies. This work complements and expands previous regional studies focused on the Southwestern U.S. and supports current efforts of local stakeholder engagement initiated by the authors.

1. Introduction

Water and energy are fundamental resources necessary for human life, economic growth, and social progress [1,2]. For example, water is used to generate electricity in hydroelectric stations, to extract and process fuel, and to cool thermoelectric power plants; on the other hand, energy is utilized to source, convey, and treat water [3]. These interdependencies are collectively referred to as the water-energy nexus (WEN) [1,3]. Numerous studies have quantified tradeoffs and synergies between water and energy systems [4–8] to support the development of integrated polices that optimize resource use [9–13] and, potentially, the achievement of sustainable development goals [14], including the reduction of CO_2 emissions [2]. These studies have been conducted at transnational [2,3], national [15,16], regional [17,18] and local scales [19,20] through qualitative [12] and quantitative [5,18,19] approaches. Despite these promising efforts, currently, the water and

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energy sectors are largely managed independently; that is, planning, management, and policy decisions are made within each sector with limited consideration of the effects of one sector on the other [11,13].

A recent report from the U.S. Department of Energy [9] highlighted an urgent need to adopt an integrated approach for water and energy management as population and climate trends are increasing the vulnerability of these two systems. This is especially true in southwestern U.S., where population has increased dramatically over the last three decades, causing a rise in energy and water needs [21]. In this arid and drought-prone region [22] with limited freshwater resources, the water supply systems are energy intensive since they rely on groundwater, inter-basin surface water transfers, and water reclamation [23]. The WEN of southwestern U.S. has been studied by Yates et al. [18] using a water resource system model. Specifically, these authors found that transitioning to low-carbon technologies and investing in energy efficiency could lead to significant water savings in southwestern states. For example, they estimated that, in the period 2010–2050, water savings in Lake Mead and Lake Powell could total ~ 2.2 billion m^3 (~1.8 million acre feet) and the groundwater storage could increase up to ~ 7 billion m^3 (~5.7 million acre feet). Results of this and similar modeling efforts are highly informative at regional scales; however, the simplifications and high level of aggregation adopted to model large regions limit the ability to draw quantitative recommendations at local scales, such as metropolitan regions [18].

One of the metropolitan areas of southwestern U.S. with strong and potentially vulnerable water-energy interactions is the metropolitan region of Phoenix, Arizona. In this desert region, population has tripled over the last 40 years, causing a change of the sectorial water end energy demands, along with associated supply portfolios and infrastructure [23–25]. Future projections suggest that population will continue to grow, as will energy demand, while more uncertainty exists regarding future water demand [26–29]. The regional water supply sources are energy-intensive and vulnerable to the impacts of climate change, and there is significant risk of shortage under drought conditions (e.g., [30,31]). As a result, water supply portfolios may be adapted in the future to meet demands, impacting the associated energy needs [32]. Furthermore, Phoenix metropolitan area utilities generate electricity mainly from fossil-fuel and nuclear power plants that require groundwater and reclaimed water for their operation [23,33]. Due to the full allocation of water rights, along with current water management rules that govern groundwater use [25], the supply available for additional water-intensive power plants is limited [11]. The development of renewable energy infrastructure has been promoted as a solution to meet future energy demands in part due to lower water requirements [5,11]; however, the cost of these investments should be properly evaluated and compared with alternative solutions.

This overview illustrates how several climatic and economic factors can significantly affect the vulnerability of the water and energy systems in the Phoenix metropolitan area, supporting the need for research that assists the development of evidence-based policies for sustainable resource management. In this study, we contribute to this need by quantifying several critical water-energy nexus interactions under a set of plausible future energy mix generation technologies. Specifically, we focus on the technological, environmental, and economic dimensions of the nexus. For this aim, we use the Long-range Energy Alternatives Planning (LEAP) platform, a tool able to simulate energy demand and supply while accounting for the characteristics of individual power plants and the energy demand of all sectors [34]. We set up LEAP by (i) focusing on the power plants managed by the two largest energy utilities of the region, and (ii) creating an energy demand structure for the residential, commercial and industrial sectors that explicitly captures the water-related energy uses. We first build confidence on our model setup by comparing simulated electricity generation and consumption against observed values reported by the U.S. Energy Information Administration (EIA) in the period 2001–2018. We then generate projections of future energy demand for the period 2019–2060 and simulate electricity generation under three fuel mix scenarios that transition more or less ambitiously to renewable energy sources. In doing so, we utilize projections of water allocations from the different supply sources simulated by Guan et al. [26] through the Water Evaluation and Planning (WEAP) platform [35] under the assumption that climate will not impact surface water resources. In addition, we simulate the most probable (or "business as usual") energy scenario under a multidecadal megadrought using water allocations also simulated by Guan et al. [26] for this extreme condition. We compare the four future scenarios by calculating key variables of the WEN, CO_2 emissions, and the associated costs.

Our work provides several novel contributions. First, we conduct analyses of the WEN at a metropolitan scale with an unprecedented level of detail in the southwestern U.S., completing and expanding recent regional studies [5,18]. Second, we integrate several data sources to rigorously parameterize and test the energy model; this effort, focused on a metropolitan region with challenges common to other areas of the world, provides useful benchmarks for future analyses at the metropolitan scale, which so far have been limited by the lack of data at this spatial granularity. To our knowledge, this is the first time that a well-calibrated energy model is used to simulate energy generation at the metropolitan scale for multidecadal time periods, with water allocations prescribed by a well-calibrated water management model to reliably quantify water-energy interactions. This effort represents a necessary preliminary step towards (i) the future coupling of the two models to simulate the two-way feedbacks between energy and water systems, and (ii) the development of model that serves as a type of boundary object [36], following efforts by White et al. [13] to understand and support policy discourse for integrated nexus governance. While focused on Phoenix, the modeling approach can be transferred to other metropolitan regions.

2. Study region and its WEN interactions

To properly capture the WEN interactions in the Phoenix metropolitan area, we selected the Phoenix Active Management Area (AMA) as our study region. The AMA is a hybrid hydrogeological-political unit of 14623 km^2 that includes the Phoenix metropolitan region and is defined by the regional groundwater basin (Fig. 1). The AMA has specific water management rules, defined by the Arizona Groundwater Management Act (GMA) of 1980 and overseen by the Arizona Department of Water Resources (ADWR). The primary goal for the Phoenix AMA is to achieve "safe-yield" by 2025 [37], which is defined as a balance between annual withdrawals from and recharges into the aquifer. The region included in the AMA has experienced rapid population growth in recent decades, increasing from about 1.4 million people in 1980 to 4.5 million in 2018. Because of existing water rights and management rules, this growth has been possible by developing new houses in cropland areas, which have sharply declined from ~1400 km^2 in 1980 to ~650 km^2 in 2009 [37]. Because of these modifications, the water and energy infrastructures have been significantly expanded and modified. The water and energy portfolios in the Phoenix AMA as of 2009 are shown in Fig. 2.

Energy in the Phoenix AMA is supplied by two utilities: Salt River Project (SRP) and Arizona Public Service Company (APS). Fig. 1 shows the corresponding service areas, along with the location of their power plants with > 100 MW of capacity (> 40 MW in the case of wind and solar). Table B1 provides details on each power plant. As presented in Fig. 2a, the energy generated in centralized power plants and delivered by APS and SRP is dominated by coal with 50% of the total energy generation. This portion includes the energy produced by the Navajo generating station, located close to the border between Arizona and Utah. This plant was built to supply electricity to the Central Arizona Project (CAP), which transports Colorado River water from Lake Havasu to central and southern Arizona through an aqueduct of 541 km. CAP owns the largest share of the Navajo generating station and is both

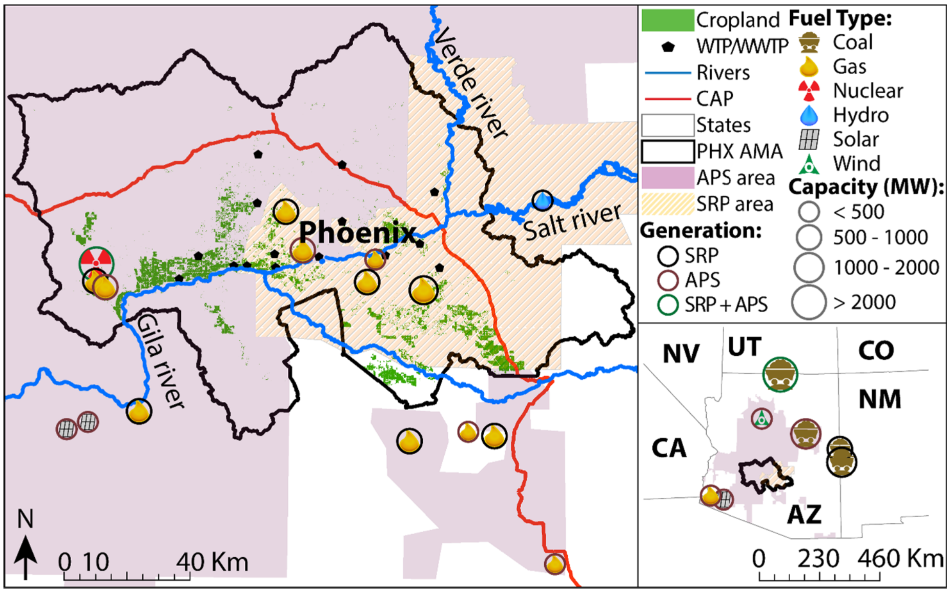

Fig. 1. The Phoenix Active Management Area (AMA) in central Arizona, along with (i) service areas of APS and SRP energy utilities; (ii) power plants located in Arizona with indication of fuel type and capacity entitlement of Arizona Public Service Company (APS) and Salt River Project (SRP) as of 2017; (iii) cropland areas in 2017; (iv) main water (WTP) and wastewater treatment plants (WWTP); (v) Salt, Verde and Gila Rivers; and (vi) Central Arizona Project (CAP) aqueduct.

the largest supplier of water in Arizona and its largest single consumer of electricity [38]. The other portion of the energy mix is almost evenly split between nuclear and natural gas. Only a very small portion (< 1%) is generated from renewable sources. Recently, SRP and APS have increased their capacity entitlement in solar and wind power sources [33,39] and purchased additional distributed renewable energy [40].

Water is currently supplied to the Phoenix AMA by four main sources, including (i) surface water from the Salt and Verde Rivers, which is managed by SRP; (ii) surface water from the Colorado River, which is provided by CAP; (iii) groundwater; and (iv) reclaimed water. Fig. 1 shows the location of surface water sources and of the plants treating potable water and wastewater. Since the creation of the AMA, the use of groundwater has declined from 47% in 1985 to 27% in 2009, while renewable surface water sources have increased from 52% to 65% (Fig. 2b; [37]). This change has been possible by the availability of CAP water starting at the end of the 1980s. Unfortunately, access to CAP water is threatened by declining Colorado River flows [22,41,42]. In the event of shortage declaration, CAP water supplies will be curtailed because of CAP's junior priority rights to Colorado River entitlements compared to California and Nevada [43].

To better illustrate the WEN interactions in our study region and support the description of the modeling framework, Fig. 3 presents a flowchart of the energy use of each component of the water life cycle. Boxes show each water source, user, or infrastructure (in bold font) and the associated energy use (in italic font). Arrows indicate water fluxes. Water from the surface and subsurface supply sources (CAP, SRP, and groundwater) is sent to the water treatment plants (WTPs) or directly to the agricultural water end-user. Energy is used for pumping CAP water and groundwater, treating water in the WTPs, and pumping water in the distribution system. Water is conveyed from the WTPs to the residential, commercial and industrial water end-users and, from these, it is sent to wastewater treatment plants (WWTPs) and water reclamation facilities (WRFs). Energy is required by the residential and commercial water end-users to heat water, by the agricultural end-user for booster pumps, and by the industrial end-users for processing (not modeled here). WWTPs and WRFs use energy in their associated treatment and pumping processes. WWTPs send a portion of the treated water to the WRFs and discharge the rest in the Salt River or into aquifer recharge sites. Reclaimed water is instead sent from the WRFs to commercial, industrial and irrigation water end-users.

3. Datasets

To set up our model of energy supply and demand, test it against historical observations, and apply it to generate future projections, we integrated datasets from 22 different regional, state, and federal agencies and utilities. The datasets and associated references are listed in Table C1, where they are grouped based on their use in the model. The data include different items, such as generation and water requirements of power plants, transmission losses, electricity sales per residential and commercial customers, energy intensity of water and wastewater treatment plants, energy expenses for pumping water, and sectorial water supply from different sources. Depending on the agency, data have different time frequency and spatial granularity. For example, some reports and databases are updated each year, while others (mainly

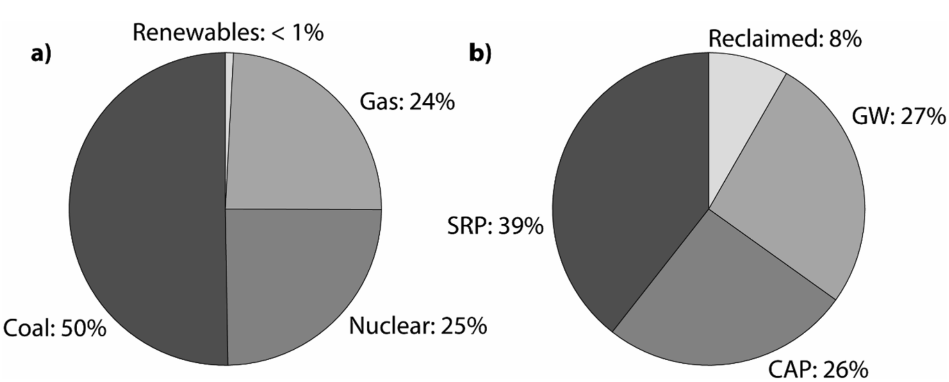

Fig. 2. Energy and water portfolios of the Phoenix AMA. (a) Combined fuel mix for energy generation of SRP, APS, and CAP in 2009, excluding distributed renewable energy (see Table B1 and [24]). (b) Water supply sources in the Phoenix AMA in 2009 [23]. GW is groundwater; CAP is Central Arizona Project; SRP is Salt River Project.

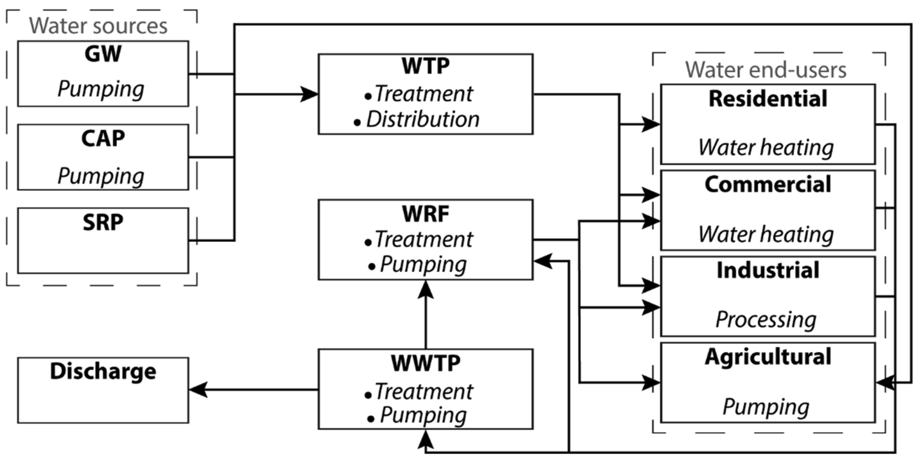

Fig. 3. Stages of the urban water life cycle in the Phoenix active management area and related energy intensive activities. In each box, bold font is used for the water source, user, or infrastructure and italic font for the energy intensive activities. GW is groundwater; CAP is Central Arizona Project; SRP is Salt River Project; WTP is water treatment plant; WRF is water reclamation facility; and WWTP is wastewater treatment plant.

those at national scale) have lower frequency. National agencies often provide state-averaged values, while regional entities provide data at county or city scale.

4. Methodology

4.1. Overview of the LEAP model

The Long-range Energy Alternatives Planning (LEAP) system is an integrated energy-economy-environment modeling tool developed by the Stockholm Environment Institute [34]. LEAP uses a hybrid bottom-up and top-down macroeconomic techniques to model energy demand and a mass balance approach and simple dispatch rules to simulate the energy fluxes from supply sources to demand end-users. Moreover, it allows for the analysis of multiple user-defined scenarios in terms of policy, economy, and environment. LEAP produces several outputs including time series of energy demand, energy supply, and CO_2 emissions, among others. In previous applications, the model has been mainly run with an annual time-step, but it can also be applied at smaller time scales to capture the seasonality in electricity supply and demand. Examples of previous LEAP applications include studies aimed at assessing CO_2 mitigation strategies [44,45], providing long-term forecast of nationwide electricity demand [46], evaluating governmental plans for future expansion of power generation capacity [47], and quantifying energy demand and CO_2 emissions of the transportation sector [48,49].

4.2. Model setup in the Phoenix AMA

We initially point out that, in this paper, we use the words energy and electricity interchangeably since electricity is the dominant form of energy in studies related to the WEN (e.g., [19,50]). We set up the LEAP model with an annual time resolution to simulate the energy production and allocation of SRP and APS, the two utilities serving the Phoenix AMA. Note that, while the area served by these companies is larger than the Phoenix AMA (Fig. 1), the population served is only slightly larger than the population residing within the Phoenix AMA (e.g., ~4.7 vs. ~4.6 million in 2017). For the Navajo generating station, we also considered the share of electricity generation owned by CAP. To model energy flows, LEAP requires defining the energy supply sources and the demand structure. These are described in the next sections.

4.2.1. Energy supply

The energy supply is represented in LEAP through modules that capture the different stages from extraction of primary resources to energy transportation to the demand sectors. Each module includes one or more processes, with characteristics specified by the user. We used two modules in our setup, including electricity generation, and electricity transmission and distribution. In the electricity generation module, we inputted the characteristics of each power plant producing electricity for APS, SRP, and CAP (see Table B1). These plants are assumed able to satisfy the energy demand in our study region (i.e., no electricity must be imported). Because of their relatively small capacities, the existing solar and wind generating stations were modeled as two distinct combined power plants, respectively. For this power system, we assumed 15% of planned reserve margin [40] and we derived the load shape from EIA ([51]; Fig. B1). For the electricity transmission and distribution module, we assumed ~5% of energy losses [52].

4.2.2. Energy demand

We created an energy demand structure with the main goal of tracking the energy embedded in all water uses and infrastructures. The demand structure includes sectors and subsectors, along with the associated end-users, activity levels and energy intensities (Table 1). For each sector or subsector, the energy demand is calculated as the product between activity level and energy intensity. A detailed description of the demand structure of Table 1 and its use for the computation of the sectorial energy demand is given in Appendix A; here, we provide a brief overview. Following EIA, we defined the residential, commercial, and industrial sectors as the three main energy consuming sectors. The energy end-users are their respective customers. For the residential and commercial sectors, we used population as activity level and derived the energy intensities from published values (see Appendix A). For these sectors, the only water-related energy use is water heating. To track the energy embedded in water, we subdivided the industrial sector into water-unrelated and water infrastructure subsectors. The latter was further subdivided into five subsectors of energy demand. The first four are water users defined by ADWR including municipal, agricultural, Indian communities, and industrial demands [23]. For these: (i) the associated energy end-users are CAP, SRP, and groundwater; (ii) the activity level is the annual water volume that is either transported, treated or pumped; and (iii) the energy intensities were derived as described in Appendix A. The fifth subsector of energy demand accounts for water treatment facilities (WWTPs and WRFs). To compute the energy demands of the industrial subsectors, we first estimated the overall energy demand of the industrial sector as a function of population and electricity price (see Eq. (A2)). Next, we calculated the energy demand in each of the water infrastructure subsectors and, finally, we computed the energy demand in the water-unrelated subsector as the difference between the total demand and the demands of the water infrastructure subsectors.

4.3. Model calibration

We validated the LEAP setup in the Phoenix AMA by comparing

Table 1
Energy demand structure of the Phoenix AMA implemented in LEAP.

Sector	Subsector level 1	Subsector level 2	End-user	Activity level	Energy intensity
Residential	–	–	Residential customers	Population	Per capita demand (kWh/capita): • Uses unrelated to water (%) • Water heating (%)
Commercial	–	–	Commercial customers	Population	Per capita demand (kWh/capita): • Uses unrelated to water (%) • Water heating (%)
Industrial	Industrial water-unrelated	–	Industrial customers	No data	Eq. (A1) minus total energy demand in the water infrastructure subsector (kWh)
	Water infrastructure	Municipal	CAP	Water volume (m^3)	• Conveyance (kWh/m^3) • Treatment and distribution (kWh/m^3)
			SRP	Water volume (m^3)	• Treatment and distribution (kWh/m^3)
			Groundwater	Water volume (m^3)	• Pumping (kWh/m^3) • Treatment and distribution (kWh/m^3)
		Agricultural	CAP	Water volume (m^3)	• Conveyance (kWh/m^3) • Booster pumping (kWh/m^3)
			SRP	Water volume (m^3)	• Booster pumping (kWh/m^3)
			Groundwater	Water volume (m^3)	• Pumping (kWh/m^3)
		Indian	CAP	Water volume (m^3)	• Conveyance (kWh/m^3) • Treatment and distribution (kWh/m^3)
			SRP	Water volume (m^3)	• Treatment and distribution (kWh/m^3)
			Groundwater	Water volume (m^3)	• Pumping (kWh/m^3) • Treatment and distribution (kWh/m^3)
		Industrial	CAP	Water volume (m^3)	• Conveyance (kWh/m^3) • Treatment and distribution (kWh/m^3)
			SRP	Water volume (m^3)	• Treatment and distribution (kWh/m^3)
			Groundwater	Water volume (m^3)	• Pumping (kWh/m^3) • Treatment and distribution (kWh/m^3)
		WWTP	WWTP	Water volume (m^3)	• Treatment in WWTPs (kWh/m^3)
			WRF	Water volume (m^3)	• Treatment in WRFs and pumping (kWh/m^3)

simulated and observed energy generation in power plants grouped according to the fuel type during the years 2001–2018. For this aim, we provided LEAP with (i) the energy intensities reported in Appendix A, (ii) population estimates from ADWR [23], (iii) annual water volume supplied by the different sources available from ADWR [23], and (iv) annual water volume treated in WWTPs available from EPA [53]. According to reports from PWCC [40] and SRP [54], the capacity of most power plants remained constant during 2001–2018 and, only in some cases, it changed with time, i.e. it was added or retired. We incorporated this information in the definition of the power plant characteristics in LEAP. For the two power plants representing all solar and all wind power generating stations, we set their merit order to one and their capacity factors to 30% and 35%, respectively. These values were defined by minimizing the difference between simulated and historical energy generation of these types of power plants. We used LEAP to simulate the annual electricity generation needed to meet the demand plus transmission and distribution losses; we then compared these values with observations from EIA to build confidence in our model setup.

4.4. Future scenarios

4.4.1. Scenario description

Once tested, LEAP was used to explore three scenarios of energy supply developed for the period 2019–2060 (Table 2). All scenarios satisfy the same energy demand and were designed following the Integrated Resource Plans (IRPs) produced by APS [33] and SRP [39], which provide information on distinct power plants that are currently scheduled to be retired in the future and where a set of possible future energy portfolios is explored through year 2032 (2037) for APS (SRP). In a "business as usual" (BAU) scenario, it was assumed that (i) all coal power plants will retire by 2045, (ii) the capacity of the nuclear plant will not change, and (iii) the renewable portfolio standard (RPS; the percent of energy generated by renewable sources) will reach 22% (50%) by 2030 (2060). These RPS targets will be achieved by adding solar plants with photovoltaic (PV) technology and wind turbines, which are the main renewable sources and technologies considered in the IRPs. The "Renewable" scenario is partly inspired by the time horizons of the RPSs of neighboring states of Nevada and California [55]. It was assumed that (i) coal power plants will retire faster than in the BAU scenario (see Table 2), (ii) RPS will rise to 50% by 2030 with the same sources used in BAU, and (iii) natural gas power plants will retire in 2060 achieving carbon-free energy generation. Finally, the "Solar" scenario takes advantage of Arizona's highly productive solar potential [56], and differs from the Renewable scenario by assuming that solar PV is the only added renewable technology. For all scenarios, in each year we (i) used the same nuclear generation capacity, and (ii) increased (decreased) the percentage of renewable sources (coal and natural gas) according to the distinct scenario goals for each year. These three scenarios assume that the availability of surface water supplies will be affected by the same climate variability observed in the past. To model the consequences of an extended period of drought, we also considered an additional BAU scenario, named "BAU-Shortage", where the water supplied by CAP and SRP is reduced as a consequence of a multidecadal drought that resembles the 'Medieval' megadrought retrieved from paleo reconstruction data in the Colorado, Salt and Verde Rivers [57]. We highlight that, given the inherent uncertainty of future projections, we have consulted local stakeholders to refine the assumptions adopted to create the scenarios through a series of workshops structured as described in White al. [58].

In the four scenarios, we forced LEAP with population projections of the Office of Economic Opportunity of the State of Arizona [59]. We obtained estimates of future water volumes supplied by the different sources to each demand sector from Guan et al. [26], who recently applied the WEAP model [35] to the Phoenix AMA. These authors (i) derived future projections of water demand for each sector up to 2060 following the trends observed over the last 25 years, and (ii) applied WEAP to compute the annual water allocations from the four supply sources to the five demand sectors under both climate conditions that will not impact surface water resources variability and the multidecadal drought. To account for the uncertainty in climate variability, Guan et al. [26] (i) generated an ensemble of 1000 time series of water volumes provided by CAP and SRP through the stochastic approach of

Table 2
Future scenarios of energy supply and associated goals. RPS is the renewable portfolio standard.

Scenario	Goals	Climate
Business as usual (BAU)	• No addition of new coal plants • Compliance with currently announced retirements • Retirement of all coal plants by 2045 • No addition or retirement of nuclear capacity • RPS of 22% by 2030 and 50% by 2060 • New renewable capacity from solar PV and wind	Conditions not affecting surface water availability
Renewable	• No addition of new coal plants • Compliance with currently announced retirements • Retirement of total coal capacity entitlement of APS by 2032 and SRP by 2037 and all gas-fueled plants by 2060 • No addition or retirement of nuclear capacity • RPS of 50% by 2030 • New renewable capacity from solar PV and wind • Carbon-free generation to be achieved by 2060	Conditions not affecting surface water availability
Solar	• New renewable capacity from solar PV • Achievement of all other goals of the Renewable scenario	Conditions not affecting surface water availability
BAU-Shortage	• Achievement of all goals of the BAU scenario	Megadrought

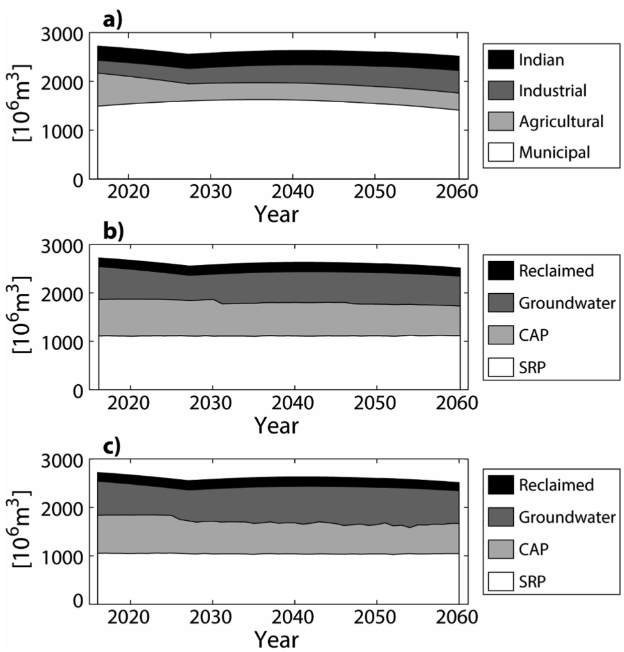

Fig. 4. (a) Annual water demand for the municipal, agricultural, industrial and Indian sectors as defined by ADWR [23]. (b) Mean of annual water volume supplied by SRP, CAP, groundwater, and reclaimed water simulated by WEAP under the same climate variability observed in the past. (c) Same as (b) but under megadrought conditions. Figure adapted from Guan et al. [26].

Gober et al. [60], and (ii) applied WEAP to simulate the allocation of water in the Phoenix AMA. Here, we forced LEAP in each scenario with the ensemble mean of the 1000 time series of water allocations simulated by WEAP. The projected annual water demand of the main sectors and the ensemble mean of simulated annual water allocations are reported in Fig. 4.

4.4.2. Scenario comparison

We compared the future scenarios through variables characterizing the WEN interactions, environmental impacts, and cost. First, we used the energy consumptions of the water infrastructure components simulated by LEAP. Second, we computed the water withdrawals by power plants. For this aim, we used LEAP outputs of electricity generation and water withdrawal rates reported by EIA [61]. Third, we used CO_2 emissions simulated by LEAP using the IPCC Tier 1 default emission factors. Fourth, we estimated the cost of each scenario. This was done by considering four types of costs: (i) overnight costs, (ii) fixed operations and maintenance (O&M) costs, (iii) variable O&M costs, and (iv) fuel costs. Overnight costs quantify the building cost of new power plants assuming no interest during construction. Fixed O&M costs account for salaries and administrative expenses; these were computed annually for all existing capacities. Variable O&M costs depend on the actual electricity generated and incorporate expenses related to water disposal and power purchase, among other items. Fuel costs are expenses related to the purchase of coal, natural gas, and uranium. The calculation of these costs is reported in Appendix D.

5. Results

5.1. Historical simulations

5.1.1. Model calibration

Prior to analyzing outputs of LEAP during the historical period, we first evaluated the reliability of the approaches proposed to estimate the sectorial electricity demand by comparing the estimated values with historical electricity sales to residential, commercial, and industrial customers in Arizona, which are available from 1990 to 2017 [62]. Results are presented in Fig. 5. The estimated residential and

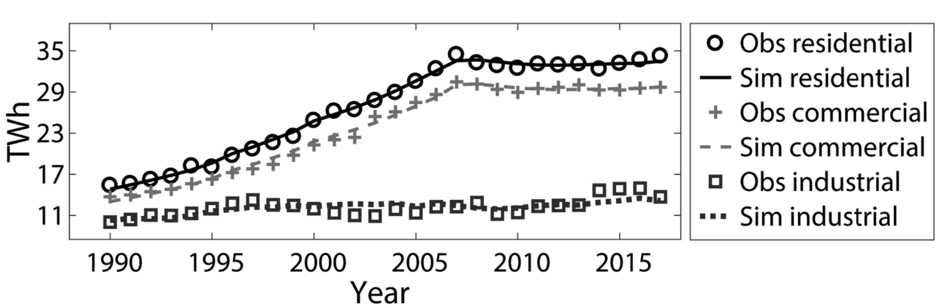

Fig. 5. Comparison between (i) observed (obs) electricity sales to residential, commercial, and industrial customers in Arizona, and (ii) estimates (sim) of energy demand for each sector obtained through the approaches described in Section 4.2.1 and Appendix A. For this verification, we used the population estimates from the Office of Economic Opportunity [59].

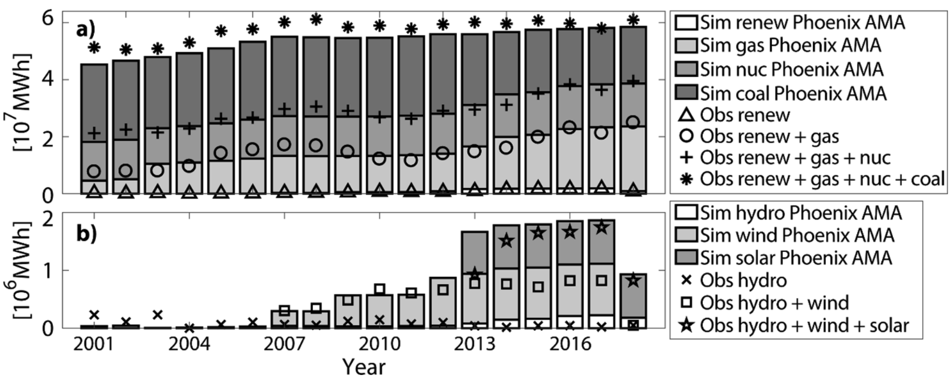

Fig. 6. Comparison between simulated (sim) and observed (obs) electricity generation of power plants aggregated by fuel type during the historical period 2001–2018. The simulations are produced by running LEAP in the Phoenix AMA, while the observations are obtained from EIA considering the capacities of APS, SRP, and CAP power plants. Panel (a) shows results for renewable, natural gas, nuclear, and coal-fired power plants, while panel (b) reports results for each source of the renewable energy, including hydroelectric, solar and wind.

commercial demands capture well the overall increasing trends (correlation coefficient, CC, equal to 0.99 in both cases; root mean square error, RMSE, equal to 0.4 TWh and 0.5 TWh, respectively). The electricity consumption of the industrial sector remained fairly constant, although with some minor fluctuations, which are largely captured by the multilinear regression model of Eq. (A2) (p-value of the F-test < 0.01, CC = 0.7 and RMSE = 0.9 TWh).

We applied the LEAP model to the Phoenix AMA during the years 2001–2018, when the energy generation in each power plant was available from EIA. We emphasize again that (i) we only considered the capacity entitlements of APS and SRP, and (ii) we computed the energy demand using population estimates for the Phoenix AMA, even if the population served by these utilities is slightly larger. Fig. 6a shows the comparison between simulated and observed energy generated by natural gas, nuclear, coal, and renewable power plants. The total energy generated is reported along with the portion of each fuel type. Given the relatively smaller magnitude of the energy generated by renewable sources, we reported the values for hydroelectric, wind and solar in Fig. 6b. We first notice from Fig. 6a that the observed total energy generated exceeds the values simulated by LEAP by a maximum of 12%. This surplus is expected because of the larger population served by the two energy utilities and the exports towards other utilities. Since these exports dropped considerably from 2016 to 2018 [63], the simulated surplus is significantly lower in those years. The simulated generation from nuclear, natural gas, and renewable sources match very well the historical generation (RMSE = 0.86 TWh, 2.33 TWh, 0.22 TWh; CC = 0.66, 0.88, 0.97; Bias = −0.06 TWh, −0.45 TWh, 0.06 TWh, respectively). The model underestimates instead the energy produced by coal-fired power plants (RMSE = 3.68 TWh, CC = 0.89 and Bias = −3.33 TWh), likely because coal power plants are located outside the borders of the Phoenix AMA and, thus, are serving customers residing both inside and outside of our study region. Fig. 6b shows that LEAP captures very well the observed electricity generated by solar, wind, and hydropower sources, except for year 2013 when the simulated solar power generation is 3.5 times the observation. This overestimation is explained because we fully included a new solar power plant (named Solana) that started operating at the end of summer. Overall, these findings provide confidence on the ability of LEAP to capture the energy generation from different sources and its allocation to the different sectors in the Phoenix AMA, thus supporting our analyses of historical conditions and future scenarios presented next. To our knowledge, this is the first time that an energy model is calibrated with this level of detail at the metropolitan scale over an extended period of time.

5.1.2. Quantification of the WEN interactions in historical conditions

The LEAP historical simulations were used to explore the water-energy interactions in the Phoenix AMA. These are visualized through the Sankey diagram presented in Fig. 7a that shows the energy fluxes in TWh from each source to the final consumption referred to year 2009, chosen as an example. Energy originates as a primary resource from different fuel types and gets converted to electricity. Due to power plants efficiencies ranging from 26% to 46% (Table B1), a significant portion (104.3 TWh; labeled Unused energy) is lost largely during electricity generation. The electricity generated is used by the residential (21.0 TWh), commercial (18.8 TWh), and industrial (12.6 TWh) sectors either for water-related or water-unrelated activities (Other). The energy embedded in water (6.6 TWh) accounts for 13% of the total energy use (52.4 TWh). The breakdown of the uses is shown in Fig. 7b (fluxes are in GWh). Water heating by residential and commercial customers is the largest use (4706 GWh), accounting for 71% of the total energy embedded in water. The rest of the energy is required to pump, move, and treat water (1950 GWh). The energy consumed by CAP (620 GWh) is more than two times the combined energy used to pump groundwater for potable use (GW; 122 GWh) and to pump groundwater and surface water for irrigation (AG; 176 GWh). The energy needed for water treatment and distribution (WTP; 651 GWh) is almost two times the energy requited to treat wastewater in WWTPs and WRFs (347 GWh).

5.2. Future projections

5.2.1. Future changes of the WEN interactions

The total energy demand adopted for the BAU, Renewable and Solar scenarios is projected to increase by 13 TWh over 42 years (Fig. 8a). Results are substantially similar under the BAU-Shortage scenario simulating the megadrought (not shown). This increase is largely due to energy uses unrelated to water and to water heating, which are directly affected by population growth. In contrast, the energy embedded in water infrastructure is expected to slightly decline (by 210 GWh for BAU-Shortage and 174 GWh for the other scenarios), as a result of the temporal changes of water demand and supply (see Fig. 4). To investigate further the changes in energy demand of water infrastructure, Fig. 8b and c show the time series of energy required by each component under the two analyzed climate conditions. Under climate conditions that will not affect surface water availability, energy consumptions for transporting CAP water (CAP) and pumping water in irrigations districts (AG) are projected to decline by 120 GWh and 67 GWh over the simulation period, respectively (Fig. 8b), mainly due to the decreasing water demand of the agricultural sector (see Fig. 4a and b). The energy consumption of the other components (GW, WTP, and WWTP) remains instead fairly constant with time (Fig. 8b) to satisfy the combined water demand of industrial, municipal and Indian sectors. The occurrence of a megadrought will reduce the availability of surface water from the gravity-fed SRP system that will be replaced by groundwater and, when available, CAP water (Fig. 4c). Interestingly, the change of water supply sources in these extreme climate conditions results in net energy reductions as high as 7% on an annual basis (Fig. 8c). This occurs because the additional energy required for groundwater pumping (maximum of additional 20 GWh annually) is offset by the lower energy needs for CAP water conveyance and potable water treatment (WTP) (maximum annual declines of 87 GWh and 68

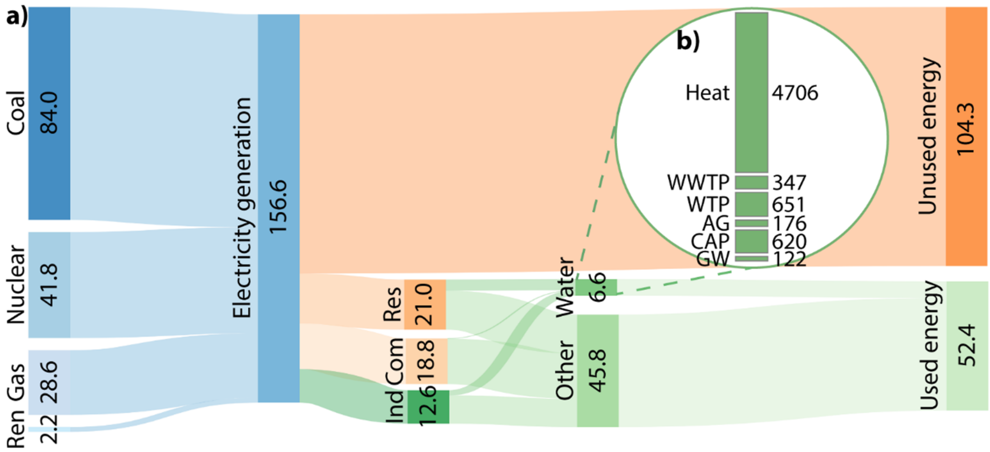

Fig. 7. (a) Sankey diagram for the energy fluxes in TWh in the Phoenix active management area in 2009. Ren is renewable energy, Res is the residential sector, Com is the commercial sector, Ind is the industrial sector, Water is the energy embedded in water, other is the energy consumed in activities unrelated to water. (b) Zoom on single activities where energy is embedded in water, with units in GWh. Differences in total values are due to rounding. Acronyms are defined in the main text.

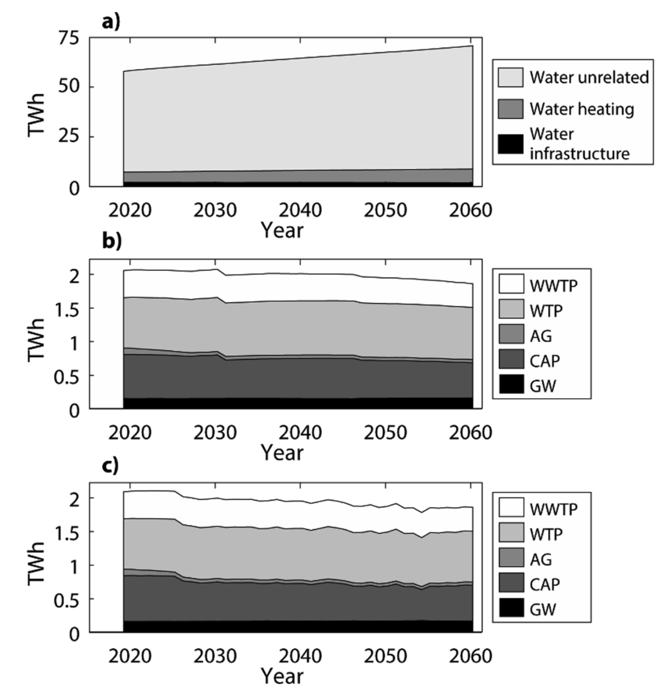

Fig. 8. (a) Energy embedded in water infrastructure, energy for water heating, and energy for activities unrelated to water in all scenarios. (b) Energy embedded in water infrastructure in BAU. (c) Same as (b) but for BAU-Shortage. Acronyms are defined in the main text.

GWh, respectively). The decrease of energy for WTPs is the result of groundwater requiring less treatment than surface water.

Turning the attention now to water needs for energy production, the simulations suggest that annual water withdrawals by power plants will decline from the initial value of 114 hm^3 (1 hm^3 = 1 million m^3) in 2018 following different trends that depend on the scenario (Fig. 9a). In BAU conditions with current cooling technologies, water withdrawals drop in 2019, then remain relatively constant through 2040 and, then, gradually decrease to 70 hm^3 in 2060 (-39% from 2018). In the Renewable and Solar scenarios (note that they have the same water needs), the decline of water withdrawals begins in 2019 and continues at a relatively constant rate of about 4 hm^3/year, reaching 45 hm^3 in 2037, then slowly decreases to 36 hm^3 in 2060 (-68% from 2018). In year 2060, the Renewable and Solar scenarios will reduce water withdrawals by 34 hm^3 compared to the BAU scenario, which represent ~2% of the total water demand (Fig. 4a). Finally, we highlight that water withdrawals in the BAU-Shortage scenario are similar to BAU since their total energy demand is almost the same.

5.2.2. CO_2 emissions

As found for water consumption, CO_2 emissions are also projected to decrease (Fig. 9b). In the BAU scenario (results are the same for BAU-Shortage), emissions decline from 31 million metric tons of CO_2 in 2018 to 10 million metric tons of CO_2 in 2060 through a step-wise curve with abrupt drops of about 9 and 3 million metric tons of CO_2 in 2020, and 2042, respectively. In these years, in fact, coal power plants are expected to be retired; for instance, the Navajo generating station is scheduled to cease operations by the end of 2019 [38]. In the Renewable scenario (results are the same for Solar), reductions are more significant: emissions fall at a relatively constant rate reaching 6 million metric tons of CO_2 in 2036 and, then, after all coal- and gas-fired power plants retire, they drop to zero in 2060, i.e. a total decarbonization.

5.2.3. Economic assessment of future energy mixes

As a next step, we provided a first-level quantification of the structural and operational costs of the future energy mixes. The aggressive alteration of the energy portfolio in the Renewable and Solar scenarios results in more capacities added and retired as compared to the BAU scenario (Fig. 10). As a consequence, overnight and fixed O&M costs of Renewable ($101 billion) and Solar ($104 billion) scenarios are higher than BAU ($59 billion). Differences in costs between Solar and Renewable scenarios originate from the use of solar PV technologies that have a higher overnight cost as compared to wind turbines [64]. Despite the higher overnight and fixed O&M costs, Renewable and Solar scenarios have lower fuel and variable O&M costs [64] (Fig. 11). These expenses total $17 billion and $20 billion for Renewable and Solar scenarios, respectively, and are much lower than the $45 billion required in the BAU scenario, where more energy is generated by more expensive fossil fuel sources. Considering all four types of costs, the investments are $111, $121, and $127 billion in BAU, Renewable, and Solar scenarios, respectively. Under BAU conditions, the supply of natural gas is the largest expense accounting for $36 billion, while overnight costs of solar power plants are the highest cost item in the Renewable (Solar) scenario accounting for $53 billion ($74 billion). Finally, we point out that costs and capacity expansion of BAU and BAU-Shortage scenarios are the same, because of similar energy supply goals and demands.

6. Discussion

6.1. Implications for future planning

The simulations presented here provide a detailed quantification of the water-energy interactions at metropolitan scale that complete and address the limitations of the regional studies of Yates et al. [18], Bartos and Chester [5], and Scott and Pasqualetti [11]. In the Phoenix Metropolitan region, additional energy infrastructure will be needed to

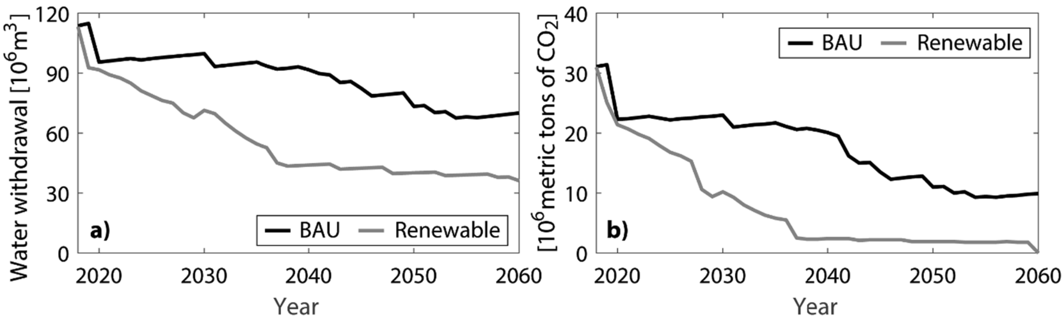

Fig. 9. (a) Water withdrawals by all power plants in BAU and Renewable scenarios. (b) CO_2 emissions in BAU and Renewable scenarios. Note that: (i) results for the BAU and BAU-Shortage scenarios are comparable because of the similar total energy demand, and (ii) results for Renewable and Solar scenarios are the same because their energy mix of carbon emitting sources is the same.

meet future energy demands that are expected to increase driven by population growth [11]. We found that energy portfolios that transition more ambitiously to renewable energy generation have two main advantages as compared to the more conservative BAU portfolio relying more on fossil fuels. First, the operation of renewable energy power plants is projected to require less water (reduction of 1330 hm^3 or 35% throughout the simulation period): this is a crucial benefit in a region with limited water resources where the expansion of energy infrastructure is limited by complicated water rights and the goal of achieving aquifer safe-yield. Second, electricity generation from renewable sources will lead to significantly lower CO_2 emissions (reduction of 436 million metric tons of CO_2 or 57%). SRP has recently approved the target of reducing CO_2 emission rates to 0.33 ton/MWh by 2035 [39]. The simulations indicate that this target would be achieved in 2031 in the BAU scenario and in 2022 in the Renewable scenario.

When considering costs, it is suggested that a more ambitious transition to renewable energy generation will require much higher structural costs but significantly lower operational costs than the more conservative BAU scenario. The total costs estimated over a time horizon of 42 years will be comparable. We highlight that our cost estimations are based on several simplifications, which should be addressed in future work. For example, (i) the delivery costs of electricity generated by the wind farms serving the Phoenix AMA, which are and will likely be mainly located in New Mexico [33], have not been included in our assessment; (ii) the costs of Renewable and Solar scenarios do not account for battery storage expenses; and (iii) the overnight costs of energy technologies, especially renewables, have been assumed as constant, but they are expected to decrease over time because of the process of “technological learning” [65].

6.2. WEN interactions and potential for synergies

In the Phoenix AMA, water-related energy uses account for about 13% of the total. Most of this energy (~71%) is required for water heating. Since future population growth will likely lead to increasing energy needs for water heating, programs targeting energy efficiency and water conservation at the residential level have the potential to induce important energy savings. For example, Bartos and Chester [5] estimated that the potential of annual energy savings from residential water conservation measures in Arizona is, on average, 1.68 TWh, an important amount when compared to the 2.03 TWh currently consumed by the water infrastructure of the Phoenix AMA (Fig. 7). The rest of water-related energy uses are needed to move and treat water (~4% of the total energy use, in line with the national average [66]). Most of this energy is needed to convey CAP water and for potable water treatment and distribution (~19%). Our future projections indicate that energy uses to move and treat water will decrease by 9% from 2018 to 2060, largely because of lower water needs for agriculture. The occurrence of an extreme drought is expected to induce slight energy savings of 1613 GWh or 2% over the simulation period, because less water will be conveyed through the CAP aqueduct and treated in WTPs. Somewhat surprisingly, this finding suggests that severe drought conditions may have minimal impacts on the energy sector. However, the larger use of groundwater resources will severely compromise the ability to achieve aquifer safe-yield; if policies restricting the use of these nonrenewable water resources will be adopted, the negative impacts on the energy sector could be significant.

6.3. Limitations and future work

The modeling approach adopted here is based on several

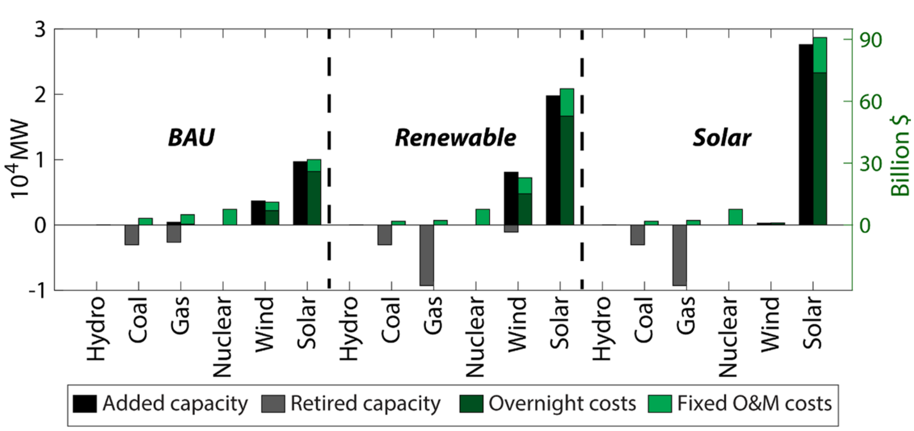

Fig. 10. Added and retired capacities (left vertical axis) grouped by fuel type along with the associated overnight costs and the fixed operations and maintenance (O&M) costs (right vertical axis). Values are cumulated from 2019 to 2060.

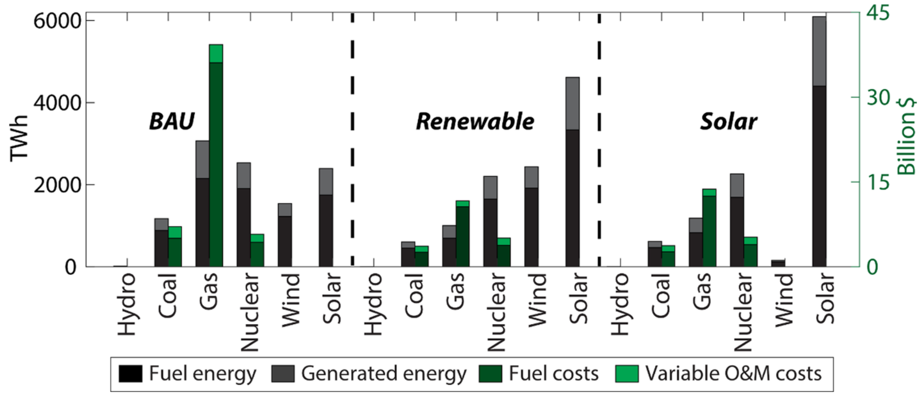

Fig. 11. Fuel energy and generated electricity grouped by fuel type (left vertical axis), along with fuel and variable O&M costs (right vertical axis). Values are cumulated from 2019 to 2060.

simplifications that we plan to address in future work. First, we used an energy model with water allocations externally calculated by a water management model. This approach should be refined by capturing the two-way feedbacks between water and energy systems. For example, water withdrawals by power plants that are simulated by LEAP should be provided to the water management model as a demand input during the simulation. The water management model, in turn, should provide LEAP with water allocations from distinct supply sources of each power plant. Dale et al. [19] demonstrated the feasibility of this modeling strategy by coupling WEAP and LEAP in Sacramento, California. Second, we applied the LEAP model at an annual time resolution; to improve the accuracy of our simulations, we plan to adopt a monthly or weekly scale that will allow (i) capturing the seasonality in energy and water demand and supply, (ii) assessing the impact of short duration extreme events such as heat waves and high-intensity storms; and (iii) modeling more accurately the dispatch from renewable technologies. Finally, we are currently representing energy uses that are not related to water through a single energy intensity. To better assess water and energy conservation programs, we should disaggregate this value into single energy uses in the commercial and residential sectors (e.g., appliances, heating, ventilation and cooling) to be able to change these intensities over time according to the energy efficiency target of each technology. Addressing these limitations in future work will allow the use of additional observed data sets to improve model setup and testing.

7. Conclusions

The analyses presented in this study in the Phoenix metropolitan region show that the LEAP platform is able to simulate quite well historical observations of energy generation and consumption at the metropolitan scale. Water heating is by far the largest water-related energy consumer, followed by conveyance of Colorado River water through the CAP aqueduct and water treatment for potable use along with distribution. Future projections of energy demand through year 2060 indicate that energy needs for water heating will increase by 35% due to population growth, but the energy required to treat and move water will decrease by 9% mainly because of the declining water demand from the agricultural sector. Simulations of future electricity generation showed that energy mix solutions that transition faster to renewable sources will reduce significantly water needs for electricity generation (35%) and CO_2 emissions (57%) as compared to the BAU scenario. The occurrence of a megadrought will result in net energy savings because less water will be transported through the energy intensive CAP aqueduct, but it will likely compromise the ability to achieve the aquifer safe-yield. The infrastructure needed to achieve these energy supply portfolios will have higher structural costs and lower operational costs as compared to the more conservative business as usual scenario that relies more on fossil fuels. By quantifying WEN interactions at the metropolitan scale, this work complements and expands previous regional studies focused on southwestern U.S. and Arizona and, thus, supports policy discourse for integrated nexus governance.

Acknowledgments

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Appendix A. Computation of sectorial energy demands in LEAP

The energy demand structure for the Phoenix AMA implemented in the LEAP model is summarized in Table 1, which reports: (i) demand sectors, (ii) subsectors with different levels that may exist within a given sector, (ii) end-users, (iv) activity level of each end-user; and (v) energy intensities of each end-user. The computation of the energy demand for each sector and subsectors is described in the next sections.

A.1. Residential and commercial sectors

The activity level and energy intensity of the residential and commercial electricity demand are population and per capita demand, respectively. The residential and commercial per capita demand were estimated from data of historical electricity sales in Arizona to residential and commercial customers in years 1990–2017 [62]. We found these values to increase from 1990 to 2007 and decrease subsequently. We used a linear regression to represent the linear growth and a negative exponential model to represent the asymptotic decline with time of the intensity of residential and commercial energy sectors:

$$y = a + bt \quad \text{if} \quad t < 2007 \tag{A1a}$$

$$y = a + b\cdot\exp(-ct) \quad \text{if} \quad t \geq 2007 \tag{A1b}$$

Table A1
Values of the regression coefficients used in the determination of residential and commercial energy intensities.

Sector	Years	*a*	*b*	*c*
Residential	< 2007	−146.84	0.08	–
Residential	≥2007	4.6	$1.1 * 10^{87}$	0.1
Commercial	< 2007	−130.43	0.07	–
Commercial	≥2007	4.3	$1.1 * 10^{87}$	0.1

where *y* is the residential or commercial energy intensity in MWh/capita, *t* is the year, and *a*, *b* and *c* are regression coefficients. Values of *a*, *b*, and *c* are provided in Table A1. The coefficient of determination R^2 for all four regression ranges from 0.84 to 0.95.

We then computed the percent of the energy demands of the residential and commercial sectors embedded in water. Previous work found water heating to be the largest energy intensive activity in these two sectors [5,67–69]. We then assumed that water heating to be the only water-related energy use and that this accounts for 22% [70] and 0.5% [71] of the total electricity use in the residential sector and commercial sectors, respectively. The rest of the electricity use was defined as uses unrelated to water in the model demand structure (Table 1).

A.2. Industrial sector

The energy demand of the industrial sector was estimated through a top-down approach. First, we derived an equation to estimate the overall energy demand of the industrial sector as a function of population and electricity price, based on previous empirical evidence [72]. The following multilinear regression was fitted to the log-transformed variables:

$$\ln(y) = 26.094 - 0.102\ln(x_1) - 0.638\ln(x_2) \tag{A2}$$

where *y* is the industrial electricity demand in kWh, x_1 is population, and x_2 is the industrial electricity rate in ¢/kWh obtained from EIA and expressed in 2017 dollars to exclude inflation effects. The energy demand in the industrial water-unrelated subsector was set up as the difference between the total demand of the industrial sector provided by Eq. (A1) and the energy demand of all water infrastructure subsectors.

The end-users of the water infrastructure subsectors are CAP, SRP, groundwater, and WWTPs (Table 1). For all end-users, the activity level is the annual water volume that is either transported, treated or pumped. Depending on the subsector, the end-users have different types of energy intensities. CAP is associated with two types of energy intensities, including water pumping and water treatment. SRP is gravity-based and only requires energy to treat water in WTPs. For the groundwater end-user, energy is needed to pump and treat water. In the agricultural subsector, all end-users utilize energy only to pump water since no treatment is required. In addition to the intensities previously described, in this subsector energy is also required to irrigate the fields from surface water sources. The computation of the energy intensities to (i) pump CAP water, (ii) pump groundwater, (iii) treat water in WTPs, WWTPs and WRFs, and (iv) pump surface water for irrigation is described in the next subsections.

A.2.1. Energy intensity of CAP water conveyance

The CAP aqueduct transports Colorado River water from lake Havasu to central and southern Arizona. Five pumping stations are required to move water to the Phoenix AMA. The energy intensity required by these pumping stations was estimated using the well-known equation $E = \frac{H\gamma}{3600 * \eta}$, where *E* is the energy intensity for water pumping in kWh/m^3, *H* is the water lift height in m, γ is the specific weight of water (9.807 kN/m^3), and η is the overall pump efficiency. The latter is the product of the pump efficiency, η_p, the mechanical transmission efficiency, η_t, and the electric motor efficiency, η_m. We assumed the same efficiencies in all pumping stations and obtained their values from previous studies. Specifically, we assumed $\eta_p = 85\%$ [6], $\eta_t = 100\%$ [6,73], and $\eta_m = 96\%$ [74], yielding an overall efficiency $\eta = 82\%$. Using this overall efficiency and $H = 250$ m, we calculated an intensity of 0.83 kWh/m^3 in the Mark Wilmer pumping station (one of the five CAP pumping stations), which is close to previous estimates of 0.78 kWh/m^3 [38], 0.85 kWh/m^3 [5], and 0.81 kWh/m^3 [75].

A.2.2. Energy intensity of groundwater pumping

The energy intensity (in kWh/m^3) required to pump water from the aquifer depends on the discharge pressure (DP), the water pumping lift (*H*, distance from the pump to the groundwater level accounting for the drawdown), and the performance rating of the pumping plant (PR) [76]. According to Martin et al. [76], a PR of 100% corresponds to a well maintained and designed pumping plant, which is known as the Nebraska Pumping Plant Performance Criteria (NPPPC). These authors also report that pumping plants often operate at PR ranging from 80% to 100% and, sometimes, exceeding 100% of the NPPPC. Martin et al. [76] provides a table that allows obtaining the energy intensity of a pumping station as a function of *H*, DP, and PR. We considered two groups of wells in our study region, including (i) wells supplying drinking water and (ii) wells located in the irrigation districts, and calculated two distinct energy intensities. For each group, a time series of *H* for the period 2001–2018 was obtained by averaging the mean annual water depth in the corresponding wells [77]. For group 1, a DP of ~110 kPa (~11 m of hydraulic head) was considered, while, for group 2, DP was set to 240 kPa (~25 m of hydraulic head). This value accounts for the additional pumping lift required for irrigation purposes once the water is pumped at the surface level (see Section A.2.4). PR was assumed identical and constant in time in both groups. We estimated this value by using state-level data of dollar expenses for pumping groundwater for irrigation in 2003 and 2008 collected by USDA [78]. Assuming an electricity rate of 0.053 $/kWh in 2003 and 0.066 $/kWh in 2008, we first converted the expenses into energy intensities of 0.34 kWh/m^3 and 0.35 kWh/m^3, respectively, and, then, we computed the values of PR from the table of Martin et al. [76] using *H* of the corresponding year and DP = 240 kPa. We averaged these two values obtaining a PR of 96%. This leads to estimated energy intensities of 0.38 kWh/m^3 and 0.32 kWh/m^3 in 2003 and 2008, respectively, corresponding to a relative error of ~10% in both years. The adopted values of PR and DP for the wells located in irrigation districts lead to an energy intensity of 0.31 kWh/m^3 that matches very well the value reported by Burt and Soto [79] for an irrigation district in California with a similar mean water depth of 46 m.

A.2.3. Energy intensity for treatment and distribution

The energy intensities of WTPs, WWTPs and WRFs were computed according to the methodology described in Pabi et al. [80]. This approach relies on typical treatment and distribution intensities in the U.S. that depend on the average flow rates and treatment processes used in WTPs, WWTPs and WRFs (see reference [81] for treatment processes used in WTPs and WWTPs in Phoenix). In addition to the treatment processes, the energy intensities of WTPs include also the energy required to pump treated water into the pressurized distribution system, but neglect the energy consumed by additional booster pumps. To validate the use of this approach in our study region, we compared the estimated average intensity of five WTPs, two WWTPs and one WRF owned by the city of Phoenix with observed values (Fig. A1). These were derived from the energy expenses of the city provided by WWRAC [82] assuming a constant electricity rate of 0.075 $/kWh. As showed in Fig. A1, the observed energy intensities do not vary significantly, thus supporting our assumption of energy intensities constant in time. The difference between estimated and observed intensities ranges from 1% to 8%.

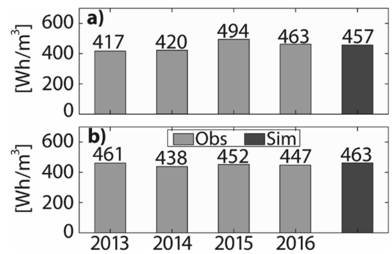

Fig. A1. Observed (Obs) and simulated (Sim) electricity intensity in (a) the five WTPs and (b) the two WWTPs and the WRF owned by the city of Phoenix.

A.2.4. Energy intensity of surface water pumping for irrigation purposes

One of the energy intensities of the agricultural subsector is related to irrigation with surface water, i.e. water provided by CAP or SRP. This intensity varies depending on irrigation types, operating pressures, crop varieties, and field areas [83]. We assumed a constant surface water irrigation intensity of 0.1 kWh/m^3 obtained from the average electricity expenses in irrigation from surface water in Arizona [78] and an electricity rate of 0.053 $/kWh reported for 2003 [84].

Appendix B. Input data for the Phoenix AMA power system

See Fig. B1 and Table B1.

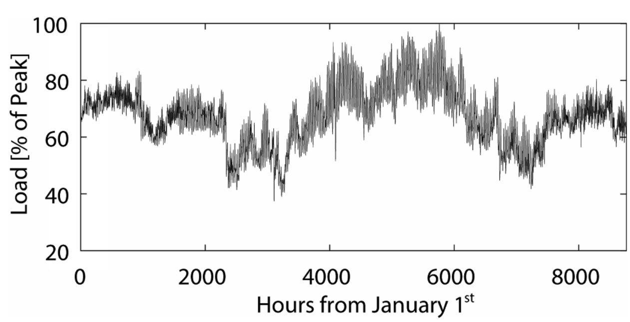

Fig. B1. Annual load shape at hourly resolution of the Phoenix AMA power system [51].

Table B1
Characteristics of power plants generating electricity for SRP, APS, and CAP implemented in the LEAP model setup.

Primary fuel type	Plant name[(a)]	Capacity [40,54] (MW)	SRP capacity entitlement [85] (MW)	APS capacity entitlement [40] (MW)	Year of first generation [24]	Merit order[(b)] [40]	Efficiency [86] (%)	Capacity factor[(c)] [87] (%)
Hydro	Horse Mesa Dam	149	149	–	1972	2	37	30
GAS	Agua Fria Generating Station (Units 1 and 3)	626	626	–	1957	3	28	30
	Kyrene Generating Station	523	523	–	1952	2	46	20
	Santan Generating Station	1219	1219	–	1974	1	44	40
	Desert Basin Generating Station	600	600	–	2001	1	45	40
	Ocotillo	333.4	–	330	1960	3	27	40
	Saguaro (Units 1 and 2)	184.5	–	110	1972	3	20	80
	Saguaro (Unit 3)	184.5	–	79	2002	3	20	40
	Sundance	605	–	420	2002	3	31	40
	West Phoenix	1207	–	997	1972	2	39	80
	Redhawk	1060	–	984	2002	1	45	60
	Yucca (Units 1, 2, and 3)	264	–	93	1971	3	29	40
	Yucca (Units 5 and 6)	264	–	96	2008	3	29	40
	Coolidge Generating Station	575	575	–	2011	3	33	80
	Mesquite Generating Station Block 1	625	625	–	2013	3	46	80
	Gila River Power Plant (Blocks 1, 2 and 4)	1650	1650	–	2005	2	39	80
Nuclear	Palo Verde Generating Station	3875	676	1146	1986	1	33	94
Coal	Coronado Generating Station (Units 1 and 2)	785	785	–	1980	1	32	90
	Navajo Generating Station	2250[(d)]	488	315	1974	1	33	92 [56]
	Craig Generating Station (Units 1 and 2)	856	248	–	1979	1	34	75
	Four Corners Power Plant	1480	148	970	1963	1	34	75
	Hayden Generating Station (Unit 2)	262	131	–	1976	1	31	75
	Springerville Generating Station (Unit 4)	385	385	–	2010	3	33	80
	Cholla	995	–	387	1962	1	31	90
Solar	Gila Bend, Foothills, and Solana	317	–	317	2013	1[(c)]	37	30
Wind	Aragonne Mesa, High Lonesome, and Perrin Ranch Wind	289	–	289	2007	1[(c)]	26	35 [88]
Total		19,313	8828	6533				

(a) Plants having a capacity over 100 MW (> 40 MW in the case of wind and solar power plants).
(b) 1st, 2nd, and 3rd merit orders in LEAP correspond to base load, load following, and peaking power plants, respectively.
(c) Value adjusted until plant simulated generation fits actual generation.
(d) CAP owns 24.3% of Navajo Generating Station, corresponding to a capacity of 547 MW [38].

Appendix C. Data sources

See Table C1.

Table C1
Overview of datasets used to setup the LEAP model in the Phoenix AMA.

Type of use	Information	Agency	Source
Determination of energy intensities	Water and wastewater treatment intensity	Water/Wastewater Rate Advisory Committee (WWRAC)	[82]
	Water treatment processes	City of Phoenix Rate Advisory Subcommittee	[81]
	WWTP average inflow and level of treatment	U.S. Environmental Protection Agency (EPA)	[53]
	Electricity expenses in irrigation	U.S. Department of Agriculture (USDA)	[78]
	Depth to groundwater	Arizona Department of Water Resources (ADWR)	[77]
	Water heating share in residential energy use	U.S. Energy Information Administration (EIA)	[70]
	Water heating share in commercial energy use	EIA	[71]
	Electricity sales to sectorial users	EIA	[62]
	Electricity rate	EIA	[84]
	Electricity sales per residential customer	Arizona Corporation Commission (ACC)	[89]
	Number of occupied housing units	U.S. Census Bureau	[90]
LEAP input	Transmission losses	EIA	[52]
	Capacity factor	EIA	[87]
	APS load shape	EIA	[51]
	Capacity entitlement of SRP	Salt River Project (SRP)	[54]
	Planned reserve margins	Pinnacle West Capital Corporation (PWCC)	[40]
	Capacity entitlement of CAP	Central Arizona Project (CAP)	[91]
	Capacity entitlement of APS	Arizona Public Service Company (APS)	[33]
	Electricity sales per residential customer	ADWR	[23]
	Number of occupied housing units	Office of Economic Opportunity, State of Arizona	[59]
LEAP calibration	Power plant generation	EIA	[24]
Post-processing	Water withdrawals by power plants	EIA	[61]

Appendix D. Cost estimation of future energy mixes

The total costs C of future energy mixes are calculated in \$ as:

$$C = \sum_{f=1}^{6} \sum_{y=2016}^{2060} [O_f \cdot N_{f,y} + F_f \cdot E_{f,y} + V_f \cdot G_{f,y} + FU_{f,y} \cdot R_{f,y}], \quad \text{(D1)}$$

where O_f is the overnight cost rate in \$/kW, $N_{f,y}$ is the new capacity simulated by LEAP in kW, F_f is the fixed O&M cost rate in \$/kW, $E_{f,y}$ is the existing capacity in kW, V_f is the variable O&M cost rate in \$/kWh, $G_{f,y}$ is the generated electricity in kWh, $FU_{f,y}$ is the fuel cost rate in \$/kWh, $R_{f,y}$ is the energy in required fuels in kWh, f is an index referring to one of the six fuel types (including renewable sources), and y is the year. Values for O_f, F_f, V_f, and $FU_{f,y}$ were obtained from EIA [64,84], while $N_{f,y}$, $E_{f,y}$, $G_{f,y}$, and $R_{f,y}$ were simulated by LEAP. All costs are actualized to year 2016.

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