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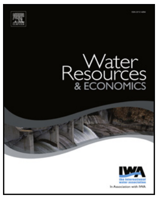

Complements of the house: Estimating demand-side linkages between residential water and electricity

Alexander Maas[a,*], Christopher Goemans[b], Dale T. Manning[b], Jesse Burkhardt[b], Mazdak Arabi[c]

[a] *Department of Agricultural Economics and Rural Sociology, University of Idaho, United states*
[b] *Department of Agricultural and Resource Economics, Colorado State University, United states*
[c] *Department of Civil and Environmental Engineering, Colorado State University, United states*

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ABSTRACT

Past studies have estimated residential demand for water and electricity in isolation, but these goods are often used as joint inputs in household production activities. As such, separately estimating electricity and water demand may lead to biased demand parameter estimates. If prices are positively correlated and goods are complements, ignoring cross-price effects will exaggerate own-price elasticity estimates, leading to inaccurate revenue and conservation forecasts. Moreover, understanding the water-electricity demand relationship will allow for synergistic conservation strategies. We propose a joint estimation procedure using 3-Stage-Least-Squares-Fixed-Effects (3SLS-FE) to highlight linkages between water and electricity and conclude that water demand, in particular, appears less own-price elastic when cross-prices are included in the demand system. Results from our study region suggest that water and electricity are gross complements (with an average cross-price elasticity of approximately -0.1). A simple simulation is included to highlight how omitting cross-price elasticities may lead to inaccurate forecasting and suboptimal decisions.

1. Introduction

The relationship between water and energy is well-documented in the water use cycle [1–3]. Most of this work implicitly focuses on the supply-side relationship of energy and water, where energy production requires non-trivial amounts of water for cooling and other activities, and considerable amounts of energy are used to treat and deliver water [4–6]. In California for example, water-related activities account for 13%–19% of total electricity use, where 5.4% of total use occurs in the home [3,7]. Beyond monetary costs, energy consumption associated with water treatment and delivery (supply-side linkages) also produces significant CO_2 emissions [7]. estimate that the urban water cycle accounts for 4% of total per capita emissions in the state of California, while [8] estimate that mandatory water restrictions in the state saved 1830 GWh of electricity and reduced CO_2 emissions by 521,000 metric tons. Yet, despite the well-documented production relationship, less is known about demand-side (end-use) linkages between electricity and water.

Given the environmental goals of many cities and the high costs associated with expanding energy and water supply capacities, understanding the impact of demand-side management on household consumption of water and electricity can lead to better holistic decision-making. Therefore, we use household-level billing data to jointly estimate household demand for electricity and water in

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* Corresponding author.
E-mail address: alexmaas@uidaho.edu (A. Maas).

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order to quantify the empirical importance of demand-side, price linkages between the two goods.

In this paper, a conceptual model of behavior is developed to describe household demand for water and electricity as intermediate inputs (herein referred to as “inputs”) in the production of household goods and services (herein referred to as “household services”). Ultimately, whether water and electricity are substitutes or complements depends on their relationship in the production of household services and the demand relationship for those services, neither of which are directly observed by the utility managers. Results from the jointly estimated demand equations are compared to estimates of own-price elasticities when water and electricity are estimated in isolation. This comparison allows us to identify the size of potential omitted variable bias created when complementarity is ignored.

In addition to using a 3-stage-least squares (3SLS) model to jointly estimate water and electricity consumption, which has rarely been used in this context, this paper provides two practical contributions to the literature. First, to the extent that water and electricity prices are correlated, ignoring the linkages across these inputs leads to biased parameter estimates [9]. If prices are correlated and goods are complements, as we hypothesize, ignoring cross-price effects will exaggerate the size of own-price elasticity.[1] This inaccuracy can lead to inaccurate demand forecasts if the current relationship between prices does not hold under future conditions. Second, a better understanding of the demand-side linkages between electricity and water can lead to improved resource management and planning. For example, water-targeted conservation programs may be part of a broader effort to manage demand for energy by reducing electricity consumption and its associated carbon emissions.

1.1. *Water and electricity demand-side linkages*

While work investigating the demand-side linkages of electricity and water is sparse, there are notable exceptions. To our knowledge—and affirmed by Ref. [10]—only one study empirically estimates household cross-price elasticities of demand for electricity and water, concluding that these inputs are mild complements with a cross-price elasticity of -0.2 [11].[2] In his study, Hansen uses a household production model, where Danish households produce household services that require water *and* energy inputs and household services that only require one of the two. While his own-price elasticity estimates are somewhat low compared to others' findings [12–14], it may be that household demand in Denmark circa 1996 differs substantially from demand in other contexts. Alternatively, the relatively low estimate could suggest that correcting for cross-prices reduces the elasticity of own-price estimates, since omitting complementary goods with correlated prices will likely bias own-price estimates upward. Herein, we expect to find a similar result.

Beyond empirically estimating cross-price elasticities, other attempts have been made to evaluate the demand relationship between electricity and water, however these attempts largely entail the supply-side relationship or impose rational decisions to minimize cost [10,15]. While these approaches are useful, they are difficult to validate and may not capture income and substitution effects. While our analysis does not allow us to separately identify substitution and income effects, we do observe the aggregate effect of real households making monthly consumption decision. In this vein [16], use a randomized controlled trial to evaluate the spillover effects of home water reports on energy use and conclude that water conservation instruments reduce summertime electricity use by between 1.3 and 2.2%, again suggesting that these inputs are complements, although price is not explicitly included in their experimental design.

Residential water elasticity estimates in the literature range from -0.1 to -1.8 [13], while electricity demand elasticity has been estimated between -0.004 and -2.01, with the bulk of estimates around -0.3 [17]. Beyond elasticity, residential water demand has been the focus of considerable research, including: determining the effects of socio-demographic characteristics, beliefs, and motivations [18–20], demand forecasting based on land-use, weather, and climate predictions [21,22], and (non-price) alternative demand management efficacy [23]. Similar analyses have been conducted for energy demand [24–28]. While each of these studies further elucidates the demand for water *or* electricity, this paper analyze the demand for water *and* electricity as functions of one another.

1.2. *Conceptualizing water and electricity in a household producer-consumer model*

To motivate the empirical analysis of this paper, we assume that households maximize utility by choosing quantities of electricity and water as part of a household-producer-consumer optimization problem [29]. For simplicity, assume that households derive utility from a market good (X) that requires neither electricity (E) nor water (W), household services that require only water (WO), only electricity (EO), water and electricity as substitutes (WES), or water and electricity as complements (WEC). A household determines the optimal level of X, E, W, WO, EO, WES, and WEC subject to a budget and time constraint, as well as the production functions relating water and electricity to the produced household services. Since the quantity of household services consumed equals the quantity produced, the solution to this problem consists of an optimal quantity of market goods, water, and electricity consumed in

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[1] For example, if water and electricity are complementary in consumption, when both prices increase, water demand falls as a direct response to its price *and* in response to the higher electricity price. A model of water consumption including only its own price would overestimate the marginal effect of water price because the water price coefficient also includes the decrease in water use from the cross-price effect.

[2] Two additional studies exist as grey literature which attempt to quantify the water-electricity-gas relationship [53,54]. Additionally, the relationship between electricity and natural gas, which are more clearly substitutes for one another, has been estimated in numerous studies [55,56], and investigations into own-price elasticity of each input in isolation are prolific.

the household. Unfortunately, the quantity of electricity and water used in each service is unobserved by the utility manager (and econometrician). Therefore, for each household, we only observe the sum of water and electricity used across the four services, W^* and E^* respectively.

In this framework, one has a finite budget to produce household services (ignoring all other market goods for the moment). This budget is split among services demanded by the household. A dishwasher or washing machine, for instance, provides cleaning services and requires both water and electricity, thus using either appliance creates a WEC service, and an increase in either water or electricity price increases the cost of this service. Lighting by comparison is an EO service whose price increases with electricity price but is unaffected by a change in water price. Importantly, while the prices of EO services do not change with water price, their relative price does. The same phenomenon is true for every service, such that demand for inputs (water and electricity) cannot be estimated accurately in isolation.

Consider the ways in which an increase in the price of electricity affects the solution to the household-producer-consumer problem. *Ceteris Paribus*, an increase in electricity price increases production costs for EO, WEC, and (possibly) WES services, which leads to a higher shadow price for these services. If EO and WO services are *complements* in demand, we expect an increase in the shadow price of EO services to reduce the consumption of WO services. If EO and WO services are *substitutes*, we expect individuals to substitute away from EO services into WO services. However, the increased shadow prices of EO and WEC services also have an associated income effect, which may reduce the overall consumption of WO goods (assuming they are normal goods). Similar rationale can be applied to WES and WEC. Ultimately, the direction and size of the cross-price effects of water and electricity depend on their production relationship in creating household services and the consumption relationship of those services. From the preceding thought experiment, it is clear that the theoretical relationship between electricity and water in a household-producer-consumer model is ambiguous, such that an empirical approach is necessary to sign and estimate cross-price elasticities. The empirical methods used to elucidate this relationship are described in the next section.

2. Methods

First, traditional two-stage-least-squares (2SLS) models of water and electricity demand are replicated. Then, a three-stage-least-squares (3SLS) method is used to simultaneously estimate electricity and water demand, accounting for cross-price linkages and correlated error terms across demand equations. Instrumenting for price is required both in the isolated and jointly estimated demand models in order to control for the simultaneity of average price and consumption quantities of each good.

2SLS models are commonly used because traditional Ordinary Least Squares (OLS) methods that regress water or electricity quantity on price cannot be interpreted as a causal impact of price on demand when increasing block rates (IBR) exist [30]. IBR pricing creates an average (and marginal) price that depends on the quantity of the good used, creating simultaneity, which violates a necessary assumption for unbiased estimation [9]. IBR's were generally introduced as a conservation tool in which the marginal price of an additional unit of water (or electricity) increases with its use, thus creating an endogeneity issue in which price is a function of quantity and vice-versa [26,31,32]. While the traditional solution, instrumenting for price via 2SLS, ameliorates endogeneity concerns, much of this work estimates demand elasticities for electricity or water in isolation, which may introduce another source of bias since these goods are often used jointly as inputs into household services.

A second complication in estimating demand is determining the price signal to which customers respond, and thus the variable for which we must instrument.[3] Average price is used in this analysis for both electricity and water bills, based on Ito’s [26] findings that consumers respond to average price rather than marginal or expected marginal price. Additionally, and in line with past studies, lagged price is used because it is the price signal consumers receive, such that the perceived average price for a month is that of the previous month's bill [13,26,67].

The final complication identified in the literature is one of unobserved heterogeneity across households [33]. Previous work and intuition suggest that houses are significantly different in their demand for water or electricity (these differences may be explained by age of home, appliance efficiency, environmental motivations, number of occupants, etc.). While some of these factors can be included as control variables, it is unlikely that the econometrician observes all relevant household characteristics. Thus, to account for the omission of unobserved household characteristics, a fixed effects (FE) approach is used in both the 2SLS and 3SLS models to average out household-level effects consistent with methods commonly used with panel data in the water/electricity demand literature [34–36]. Despite the possibility of inefficient estimates, FE is preferred to random effects (RE), because RE requires the stringent assumption that each random effect is uncorrelated with all explanatory variables in each time period. By comparison, FE models estimate deviations (in each period) from the household's average consumption over time. While this method prevents us from estimating the effects of time-invariant characteristics, it does not impede the goal of this paper, to estimate the own- and cross-price elasticities of water and electricity in household demand.

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[3] Some authors suggest that the theoretically consistent approach is to include a term for both marginal price and a block difference term [57–59]. Others use perceived price [60] or average variable price [18]. Other researchers have found that the mere presence of an IBR decreases consumption regardless of price [61] while other work suggests that the tractability of the unit price displayed on the bill significantly affects individuals' responses [62].

2.1. *Two-stage-FE least squares estimation*

The 2SLS method estimates the impact of price on the quantity demanded for each input in two independent models. We begin with this method to obtain estimates for comparison, in order to determine the impact of jointly modeling electricity (e) and water (w) demand. Let y_{it}^{j} be the log of demand for input $j \in \{e, w\}$ by household i in period t and $\bar{y}_{i}^{j}$ be the average log of demand for each individual across all periods. The 2SLS-FE specification used in this analysis postulates that y_{it}^{j} depends on the log average price of input j on last month's bill, p_{it-1}^{j}, days of service in bill period t, l_{it}^{j}, total precipitation experienced by household i in time t, r_{it}^{j}, average daily temperature, c_{it}^{j}, wildfire actively burning, f_t, and a vector of dummies for the month in which the bill was issued m_t'. Average temperature was calculated as max daily temperature plus minimum temperature, divided by 2, summed across the bill period, and divided by the days of service in that bill period (l_{it}). We also include the interaction of weather variables with a dummy variable for summer months (s_t) to account for the dependence of outdoor water use on weather patterns in the irrigation season. Lastly, a dummy variable was included to account for the High Park fire, which burned 87,000 acres just west of town in the summer of 2012. During the fire, citizens were cautioned to stay indoors to avoid ash and smoke, which likely increased energy use via AC and air purification systems. The presence of fire may also affect water consumption, but the mechanism and direction of the affect is less clear. Staying indoors during the fire may increase indoor water use, but it may also decrease lawn and garden watering.

Let $\breve{y}_{it}^{j}$ be the deviation of log demand for each household in each period from average demand ($\breve{y}_{it}^{j} = y_{it}^{j} - \bar{y}_{i}^{j}$). Prices ($\breve{p}_{it}^{j}$), precipitation ($\breve{r}_{it}^{j}$), temperature ($\breve{c}_{it}^{j}$), and dummy variables ($\breve{m}_t'$, $\breve{f}_t$, $\breve{s}_t$) are each calculated similarly, such that each variable represents that periods deviation from household $i's$ mean across all periods.

Given the above, household i's demand for service j in time t can be expressed as:

$$\breve{y}_{it}^{j} = \beta_0^{j}\breve{p}_{i,t-1}^{j} + \beta_1^{j}\breve{l}_{it}^{j} + \beta_2^{j}\breve{r}_{it}^{j} + \beta_3^{j}\breve{c}_{it}^{j} + \beta_4^{j}\breve{s}_t\breve{r}_{it}^{j} + \beta_5^{j}\breve{s}_t\breve{c}_{it}^{j} + \beta_6^{j}\breve{f}_t + \breve{m}_t'\phi^{j} + \varepsilon_{it}^{j} \tag{1}$$

where β^{j}'s and ϕ^{j}'s are coefficients to be estimated and ε_{it}^{j} represents random error. Price is instrumented in the first stage by regressing $\breve{p}_{i,t-1}^{j}$ on all exogenous variables from the second stage, as well as mean-differenced price of block one for each input, $\breve{\rho}_{t-1}^{j}$, and the days of service for the corresponding bill ($\breve{l}_{i,t-2}^{j}$). Because rates are determined by City Council and the days of service for each bill vary over time—and are largely determined randomly by the utility billing cycle—both variables are correlated with average price but exogenous to the household and uncorrelated with ε_{it}^{j}. Further, since price and quantities consumed are expressed in logs, the estimated coefficients on prices represent an estimate of own-price elasticities. These 2SLS-FE estimates provide a benchmark with which to compare the estimates of the joint model described below.

2.2. *Three-stage-FE least squares estimation*

While the 2SLS-FE method is conventionally used in the literature, if $corr(p_E, p_w) \neq 0$, 2SLS elasticity estimates from models that omit cross-prices are erroneous. Therefore, we model water and electricity demand as a system of equations, which estimates water and energy consumption jointly as a function of both input prices, while allowing for correlation of error terms across demand equations.

The 3SLS-FE model developed herein simultaneously estimates the demand for electricity and water.[4] Similar to the 2SLS, we use rate dummy variables and lagged days of service as instruments for price in each equation.[5] The model simultaneously estimates the following four equations, with variables defined identically to those used in the 2SLS-FE model.

$$\breve{y}_{it}^{w} = \beta_0^{w}\breve{p}_{i,t-1}^{w} + \beta_1^{w}\breve{p}_{i,t-1}^{e} + \beta_2^{w}\breve{l}_{it}^{w} + \beta_3^{w}\breve{r}_{it}^{w} + \beta_4^{w}\breve{c}_{it}^{w} + \beta_5^{w}\breve{s}_t\breve{r}_{it}^{w} + \beta_6^{w}\breve{s}_t\breve{c}_{it}^{w} + \beta_6^{w}\breve{f}_t + \breve{m}_t'\phi^{w} + \varepsilon_{it}^{w} \tag{2}$$

$$\breve{y}_{it}^{e} = \beta_0^{e}\breve{p}_{i,t-1}^{w} + \beta_1^{e}\breve{p}_{i,t-1}^{e} + \beta_2^{e}\breve{l}_{it}^{e} + \beta_3^{e}\breve{r}_{it}^{e} + \beta_4^{e}\breve{c}_{it}^{e} + \beta_5^{e}\breve{s}_t\breve{r}_{it}^{e} + \beta_6^{e}\breve{s}_t\breve{c}_{it}^{e} + \beta_6^{e}\breve{f}_t + \breve{m}_t'\phi^{e} + \varepsilon_{it}^{e} \tag{3}$$

$$\breve{p}_{i,t-1}^{w} = \gamma_{i0}^{w} + \gamma_1^{w}\breve{\rho}_{t-1}^{w} + \gamma_2^{j}\breve{l}_{i,t-2}^{w} + \nu_{it}^{w} \tag{4}$$

$$\breve{p}_{i,t-1}^{e} = \gamma_{i0}^{e} + \gamma_1^{e}\breve{\rho}_{t-1}^{e} + \gamma_2^{j}\breve{l}_{i,t-2}^{e} + \nu_{it}^{e} \tag{5}$$

Note that days of service (l_{it}^{j}), precipitation (r_{it}^{j}), and temperature (c_{it}^{j}), are specific to the bill period and may vary if the bill period for water and electricity differs.[6]

2.3. *Data and parameterization*

This section describes the data used to estimate both the 2SLS-FE and the 3SLS-FE models described above and provides a brief

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[4] 2SLS estimation including prices for both inputs would provide similar results, but it would be less efficient than the 3SLS model.

[5] See Ref. [63] for a formal presentation of the model's identification requirements and assumptions.

[6] The sample was limited to observations with bill dates within three days of one another. Some observations did not have similar bill periods for water and electricity and were excluded from the sample because we cannot determine the cause of this discrepancy. Additional cleaning was also necessary to remove extreme values and obvious errors. Frequency plots and the logged mean of consumption remain similar before and after cleaning, changing by less than 0.4%. The specific cleaning rules can be provided upon request.

explanation of the billing structure. The analysis avoids censored data complications associated with demand studies that include zero quantities of particular goods [37,38], by dropping any observation with zero consumption for either water or electricity. Homes without utility consumption are likely vacant or indicate a billing error and are not indicative of household demand. This decision should not meaningfully affect our results so long as home vacancies within a season are random in nature.[7]

Consistent with previous studies [13,17], weather is modeled as a primary driver of deviations in demand. Total monthly precipitation and average mean daily temperature over each billing cycle were calculated using data from Ref. [39]. Daily weather data were match to each billing period to create total precipitation and average daily temperature variables for each household in each bill period.

Billing records from a large utility in Colorado provide data on monthly electricity and water consumption and bill amounts, for roughly 22,000 households with relatively complete billing records (at least 36 monthly bills) over the period 2006–2014. Bills with fewer than 25 days or more than 35 were excluded because we could not identify why these anomalies occurred.[8] Additionally, billing accounts with more than two associated taps were excluded, since this feature may indicate landlords or rentals that do not directly receive bills.

The period of our sample includes significant price variation, with twelve changes in rate structure (five in water pricing and seven in electricity). A summary of the annual rate structures is provided in Table 1. For water, the IBR structure includes three blocks with incremental increases in price. Block price thresholds were set at 7,000gal. and 13,000gal. for the entire period of our sample. Prices increased for each block across the years in our sample. For example, block prices in 2006 were $1.87, $2.15, $2.48 per thousand gallons in block one, two, and three, respectively. By 2014 these prices increased to $2.38, $2.74, and $3.15, respectively.[9]

After 2011; electricity prices exhibit a similar upward trend. Although for 2006 to 2011 block pricing was not in place (each block price was given the same value for this period in our model). Block price thresholds were 500 kWh and 1000 kWh for the years in which they exist, however the price at each block varied between summer (June to September) and winter (October to May) months. For example, in 2014 summer block prices were $0.0896, $0.106, and $0.140 per kWh in summer, but decreased to $0.0824, $0.0864, and $0.0951 in winter months.

Fig. 1 illustrates average monthly consumption for electricity and water over the period of observation. Note that both water and electricity use have slight downward trends, water has one large peak in summer, and electricity consumption peaks both in winter and in summer. Fig. 2 illustrates average monthly total bills for water and electricity, note that electricity bills were increasing during this time, while water bills remained relatively flat.

Summary statistics for variables used in the analysis are presented in Table 2. Average per capita per day consumption is approximately 120 gallons and 320 kWh for water and electricity respectively, assuming 2.4 persons per household.

3. Regression results and demand scenarios

3.1. Elasticity and demand estimation

Table 3 presents coefficient estimates for the traditional approach of estimating electricity and water demand separately (columns 1 & 2), as well as the coefficients estimated jointly using the system of equations presented in Section 2 (columns 3 & 4).[10] For all models, we report bootstrapped standard errors clustered at the household level to allow for potential dependence across time. Consistent with expectations, we find a moderate correlation between electricity and water price ($\rho_{p_w p_e} = 0.32$), and results from Table 3 suggest that water and electricity are related such that demand for each responds to a price change of the other.

Electricity and water are gross complements,[11] although cross-price elasticities are relatively small in magnitude. Water demand is moderately inelastic with an own-price elasticity of -0.594 and a cross-price elasticity of -0.155. Electricity by comparison, is very inelastic in both own-price (-0.179) and cross-price (-0.051).

It is also worth noting that the cross-price elasticities are similar across demand functions (difference of approximately 0.1), but not identical, which suggests a potentially differential income effect across input goods. The most plausible explanation for the limited income effect is the relatively insignificant share of income spent on electricity or water such that consumers do not experience a noticeable change in purchasing power as dur to price increases, but more work is necessary to validate this conclusion.

Our results also suggest that modeling demand for water and electricity in isolation may lead to erroneous estimates, but the bias is small. As expected, given the hypothesized complementary relationship between household water and electricity use, estimating each in isolation produces more elastic estimates than estimating demand jointly. When estimated in isolation (Table 3, columns 1 &

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[7] Across the raw data, the percent of vacant homes to homes using power or water remains relatively constant across months at approximately 1%. We found no evidence that house characteristics are meaningfully correlated with these vacancies.

[8] Anecdotally, the utility believes that the use of smart meters has essentially randomized the billing cycle across households (since meters are no longer read neighborhood by neighborhood) and that billing period should be approximately 30 days.

[9] Because billing method and price perceptions may affect consumption decisions [62], it is worth noting that bills from the utility present line item sub-totals by water and electricity tier and "New Charges this billing period" in bold at the bottom of the bill.

[10] While Equations (2)–(5) represent the model used in our analysis (Results presented in Table 3), many specifications were tested for robustness. Qualitative results remain consistent across model specifications, although the relative size of own-price elasticity ranged from -0.42 to -0.69 for water and -0.10 and -0.26 for electricity. For cross-prices, water demand ranged from -0.15 to -0.30 and electricity demand ranged from -0.05 to -0.20. Results from a full set of specifications can be made available upon request.

[11] For a more detailed discussion of gross versus net complements, see Ref. [64].

Table 1
Rate structure.

Year	Water (per 1,000 gal)				Electricity (per 100 kWh)			
	Block 1	Block 2	Block 3	Fixed Charge	Block 1	Block 2	Block 3	Fixed Charge
2006	$1.87	$2.15	$2.48	$12.72	$6.00	$6.00	$6.00	$3.69
2007	$1.97	$2.26	$2.60	$12.72	$6.00	$6.00	$6.00	$3.69
2008	$1.97	$2.26	$2.60	$12.72	$6.39	$6.39	$6.39	$3.69
2009	$1.97	$2.26	$2.60	$12.72	$6.68	$6.68	$6.68	$3.91
2010	$2.04	$2.35	$2.70	$12.72	$7.18	$7.18	$7.18	$4.20
2011	$2.11	$2.42	$2.78	$13.60	$7.97	$7.97	$7.97	$4.14
2012	$2.11	$2.42	$2.78	$13.60	$8.34/$7.82	$10.01/$8.22	$13.36/$9.10	$4.75
2013	$2.19	$2.52	$2.89	$14.14	$8.76/$8.01	$10.44/$8.50	$13.79/$9.38	$4.75
2014	$2.38	$2.74	$3.15	$14.14	$8.96/$8.23	$10.63/$8.63	$13.98/$9.52	$4.75

Note: Block and seasonal pricing for electricity began in 2012. Higher prices reflect summer rates, while lower prices reflect winter rates.

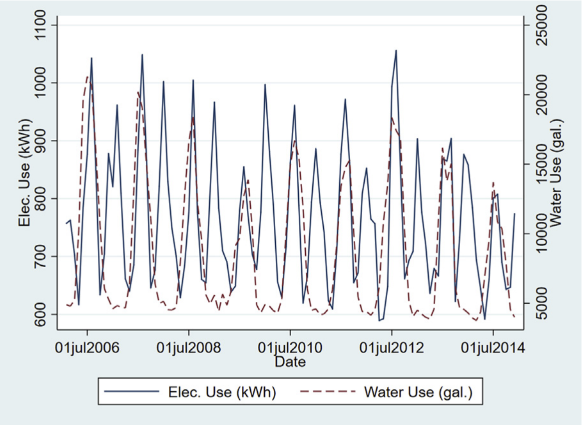

Fig. 1. Average monthly consumption.

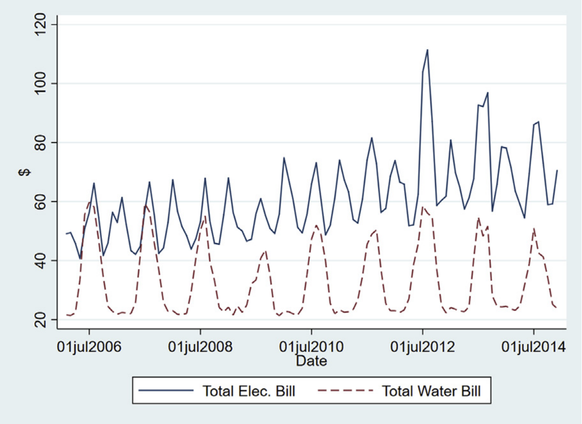

Fig. 2. Average monthly bill.

2), both water and electricity demand appear more own-price elastic (-0.785 and -0.183).[12] Our result suggests that improper specification of demand could lead utility managers to overestimate the effectiveness of water price as a conservation tool for water use. Our result suggests that improper specification of demand could lead utility managers to overestimate the effectiveness of water price as a conservation tool for water use. The omitted variable bias in electricity demand is noticeably smaller, such that own-price coefficients between columns 2 and 4 are not different in an economically significant way. While the magnitude of own-price bias

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[12] Formal tests of coefficient equality are, to our knowledge, not possible across non-nested models, but it is worth noting that point estimates from the 2SLS are more than 4 standard deviations away from point estimates in the 3SLS in water demand, and within 2 deviations in electricity demand.

Table 2
Summary statistics (seasonal).

n = 1,750,309

Variable	Mean	Std. Dev.	Min	Max
Water Use (gal.)	8,646	8,379	1	439,820
Electricity Use (kWh)	763	478	1	7999
Water Avg. Price ($/1,000gal.)	6.20	4.46	0.02	14.1
Elec. Avg. Price ($/kWh)	0.081	0.012	0.022	4.84
Precipitation (mm)	2.89	3.12	0	17.3
Avg. Temp. (C)	9.34	8.78	−8.31	24.2
Length of Bill Period	30.4	2.00	25	35

Table 3
Regression results.

Variables	(1)	(2)	(3)	(4)
	2SLS-FE		3SLS-FE	
	Water	Elec.	Water	Elec.
Water Price	−0.785***		−0.594***	−0.051***
	(0.0039)		(0.0073)	(0.0060)
Electricity Price		−0.183***	−0.155***	−0.179***
		(0.0017)	(0.0066)	(0.0069)
Avg. Temp. (C)	0.0319***	−0.0053***	0.0316***	−0.0058***
	(0.0002)	(0.0001)	(0.0002)	(0.0001)
Temp.*Summer	0.0038***	0.0121***	0.0035***	0.0117***
	(0.0001)	(0.0000)	(0.0001)	(0.0001)
Precipitation (mm)	−0.0027***	0.0002***	−0.0026***	0.0002***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Precip.*Summer	−0.0004***	−0.0008***	−0.0004***	−0.0008***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Length of Bill (days)	0.0375***	0.0337***	0.0363***	0.0341***
	(0.0002)	(0.0001)	(0.0002)	(0.0001)
Wildfire (0,1)	0.041***	0.106***	−0.594***	0.185***
	(0.0021)	(0.0014)	(0.0025)	(0.0015)
n = 1,750,309				
# households = 22,600				

Coefficients for month dummies and intercept are omitted for succinctness.
Significance is determined by clustered standard errors.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

differs across demand estimates, the negative and significant cross-price coefficient suggests that synergistic opportunities exist to conserve one utility service by increasing prices of the other.

3.2. *Future scenarios*

Given the well-established relationship between electricity and water in production, and our current findings of a similar relationship in residential consumption, policymakers should pay special attention to the impact one good has on the other. When projecting supply needs, forecasting revenue, and setting prices, water and energy utilities should collaborate such that optimal pricing strategies account for cross-sectoral linkages. Our results suggest that utilities can substantially promote water conservation by increasing the price of electricity, and perhaps *vice versa*. Thus, conservation in both inputs is possible even when a price lever only exists for one. This implication may be of particular interest in situations where 1) changing the price of one utility service is more politically feasible than changing the other, or 2) service providers cannot separately meter across multiple uses (apartment buildings for instance may only have a single water tap to the building but have individual electricity meters).

To illustrate the benefit of jointly considering energy and water use, we provide a simple 10-year simulation of predicted summer and winter electricity-water demand under varying price and estimation scenarios, assuming constant elasticity. Fig. 1 presents six projections for electricity and water demand. The grey solid line uses coefficients from the 2SLS-FE models to project future water use based on an annual 3% increase in its price (many utilities have the goal of keeping rate increases below 3% annually; as such, we use this rate increase for both water and electricity price scenarios). The grey dashed line uses the coefficients from the 3SLS-FE model to project future consumption based on an own-price increase of 3%, and the black dashed line projects use based on a 3% increase in both electricity and water price.

Fig. 3 illustrates the divergent predictions obtained when including or ignoring cross-price effects in demand estimation and

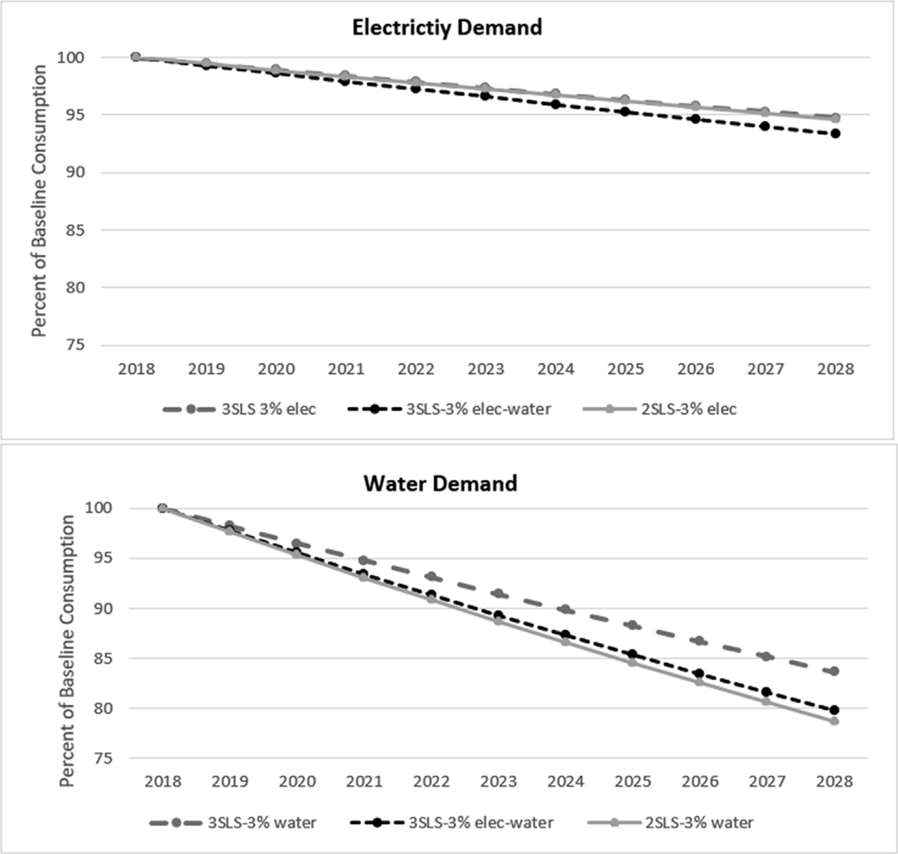

Fig. 3. Demand Projections: *Projected demand for water and electricity as a % of current use under 3% annual increases in water price, electricity price, and in both prices. 2SLS use coefficients estimated in isolation and 3SLS use coefficients estimated jointly.*

forecasting. Under the 2SLS estimates, projected water consumption is 78.7% of current use by 2028. Using the 3SLS estimates, water use is less elastic and projected at 83.6% of current consumption by 2028. Thus, if estimates from the 3SLS-FE are correct, utility managers would over project savings from water price increases by 5% points annually. Projected demand under increases in both electricity and water prices is 79.8% of current use by 2028. A similar but smaller phenomenon can be seen in electricity use. Results generally suggest that ignoring cross-price effects in estimation may not yield large differences in projections so long as both prices continue to move together. If this relationship does not hold in the future however, using elasticities from isolated demand estimation will significantly over-estimate the savings due to own-price increases.

4. Discussion and conclusion

Nationally, roughly 4% of the United States' total electricity generation is for water-related activities [40,41]. Water scarcity continues to grow across the southwestern United States [42], and energy production continues to impose negative on local and global communities externalities [43–45]. Revenue shortfalls for many utilities and uncertainty around supplies and production are also a chief concern [46]. cite the importance of including behavioral science in crafting a future with low emissions and reliable resource supply.[13] A similar sentiment exists among the physical and natural water sciences [47]. This paper fills a gap in our current understanding of the demand-side linkages between electricity and water, which may improve water-energy planning and management. This improvement may be particularly valuable if past estimates, which do not account for these linkages, provide biased results that lead to suboptimal investment and planning decisions. In our sample city, this bias is relatively small, although notably higher in water demand estimation than in electricity.

Given the significant interest among utility providers in understanding consumer choices, encouraging conservation, and correctly forecasting consumption and revenue, our results have significant implications for policy design. Failing to account for future electricity rate increases leads to inaccurate water use forecasts (and maybe vice-versa). Additionally, the benefits of water (electricity) conservation programs extend beyond just those associated with water (electricity) savings. Many utilities and city planners

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[13] Yet for every research dollar spent on behavioral demand side energy research, $35 is spent on energy supply and infrastructure [65,66].

are moving away from the traditional, utility service provision model, to one of integrated management, in which water, electricity, and other resources are managed holistically [48–51]. Understanding the relatedness of these inputs gives utility managers the ability to coordinate pricing, conservation, and infrastructure for common goals.

Finally, when we consider the amount of energy required to treat water and the water that is required to produce energy, our results have implications for greenhouse gas emissions and other negative economic externalities associated with consuming fossil fuels. While more work is needed to provide robust carbon emission estimates, a back of the envelope calculation suggests that increasing municipal water price by 10% could reduce total electricity consumption in the Southwest by over 1.3 million megawatt hours per year.[14] Given current energy production methods, this amount of electricity savings translates to over 1 million metric tons of carbonprevented from entering the atmosphere each year,[15] not including additional savings from supply-side energy reductions from decreased water demand [8].

Future work to further understand the demand-side linkages of electricity and water should disentangle the production of household services that require electricity and/or water as inputs, and the associated seasonality of water-electricity relatedness. To the extent that households demand different services across seasons, the underlying relationship between electricity and water may shift significantly from winter to summer months. Moreover, utilities could benefit greatly from a clearer understanding of how consumers relate bill information to prices. Considerable work in this area has been conducted, but little consensus exists. Research could also be expanded to include water and electricity as it relates to perceived versus actual use in the context of changing prices, since current research suggests that customers have a poor understanding of the inputs required for each household service [52,68].

A limitation to this study is the omission of data on natural gas consumption in the home. A particularly important energy-water connection comes from the need to heat water. Homes in our study region almost exclusively use natural gas for water (and space) heating. A logical extension of this work would include an analysis of the effect that gas heating has on the electricity-water relationship. Due to the lack of empirical work in this area, it remains to be seen how cross-price elasticity estimates may differ across locations due to differences in heating technologies, population density, ecoregions, billing methods, etc. Therefore, careful consideration must be given before using these estimates in other contexts and locations. Despite these limitations and needs for future work, the analysis presented here provides policymakers with information necessary for synergistic pricing policies and a more thorough understanding of the demand-side relationship of water and energy.

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Appendix A. Supplementary data

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[14] We assume that annual per household electricity use is ~14,000 kWh, total population of the Southwest is 44,800,000, and households are comprised of 2.4 people. Thus, total megawatt hours consumed is ~261 million mWh). Using our estimates, a 10% change in water price leads to a 0.5% change in electricity use (~1.3 million mWh).

[15] This number was calculated using the EPA's Greenhouse Gas Equivalencies Calculator.

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